

TECHNICAL REPORT R-848

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## SEAFLOOR CONSTRUCTION EXPERIMENT, SEACON II

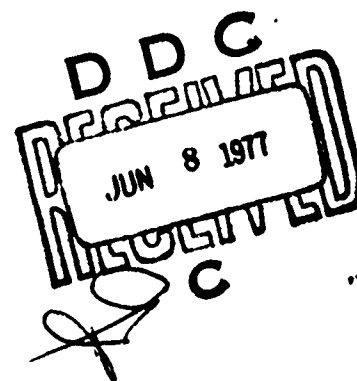
AN INSTRUMENTED TRI-MOOR FOR EVALUATING UNDERSEA  
CABLE STRUCTURE TECHNOLOGY

by

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December 1976

CIVIL ENGINEERING LABORATORY  
NAVAL CONSTRUCTION BATTALION CENTER  
PORT HUENEME, CA 93043

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The authors wish to acknowledge the efforts of the many individuals and organizations who contributed to the success of the SEACON II experiment.

Messrs. Melvin Stern and Gene McMahan designed and monitored the fabrication of much of the SEACON II mechanical hardware. Mr. Floyd Nelson was the key individual in the design, fabrication, and operation of the SEACON II instrumentation system. The navigation and current measuring equipment was operated and maintained by Mr. Gerald Duffy. Mr. Philip Zubiate, in addition to his many duties as project technician, conducted the tests leading to the selection of the EM cable termination and splicing techniques. Mr. Joseph Graham pressure tested components prior to implant. Dr. Francis Liu participated in developing the implant technique and in providing static and dynamic loading predictions for implant. Mr. James Jenkins consulted on materials selection and designed the cathodic protection system. The dual release mechanism for the current meter moors was developed by Mr. Ronald Brackett. LT James Halwachs developed the neutral float current measurement device. Mr. Henry Lingg was the captain and pilot of the implant vessel and the cruise leader on the current meter installation and recovery cruises. Mr. Stanley Black prepared the detailed implant plan and was implant director. Messrs. Robert Taylor and Philip Babineau prepared and helped install the experimental explosive embedment anchors. CEL technical support branch personnel fabricated and assembled the majority of the mechanical hardware and implanted the structure. LTs Anthony Parisi, Gary Sniffin, and Richard MacDougal and the CEL diving locker personnel participated in the structure implant, installed and recovered the current meter moors, and performed underwater repairs and maintenance on the SEACON II structure. Mr. Richard Malloy provided many helpful suggestions and valuable guidance throughout the course of the project. Programs for reducing current meter and structure sensor data were prepared by Mr. Rudiger Von Nathusius and Mrs. Rita Brooks. Messrs. Earl Buck and Leonard Woloszynski reduced and analyzed the acoustic position data. Mr. Robert Welsh, NUSC, New London, coordinated the NUSC experiment conducted in SEACON II. The design and fabrication of the command, control, and recording equipment supplied by NUSC, New London was coordinated by Mr. Robert Hartley. SUBDEVGRUONE personnel provided the services of deep submersible vehicles *Seacliff* and *Turtle*. Inspection and recovery services using the *CURV III* submersible were provided by NUC, San Diego. PMTC, Point Mugu provided site surveillance as well as other services to the project. Dr. Richard Skop of NRI, provided consultation on the use of DESADE for predicting SEACON II structure response. Dr. T. Sarpkaya of the Naval Postgraduate School and NSRDC personnel provided drag coefficient measurements on SEACON II cable specimens; Mr. Dallas Meggitt, C.I.L., arranged for and coordinated these drag coefficient measurement tests.

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**METRIC CONVERSION TABLE**  
**(International System of Units)**

1 foot	= 0.3 meter (m)
1 inch	= 2.5 centimeter (cm)
1 kip	= 4,448.2 Newton (N)
1 knot	= 0.5 meter per second (m/s)
1 mile	= 1.6 kilometer (km)
1 pound	= 0.4 kilogram (kg)
1 psi	= 6.9 kilopascal (kPa)
1 slug/ft <sup>3</sup>	= 515.4 kilogram per meter <sup>3</sup> (kg/m <sup>3</sup> )
1 ton	= 907.2 kilogram (kg)
Temperature, °C	= (°F - 32)/1.8

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large, fixed subsea cable structures. The SEACON II structure consisted of a delta-shaped module tethered by three mooring legs in 2,900 feet of water. The top of the structure was positioned approximately 500 feet below the surface. The mooring legs were 4,080 feet long, with each arm of the delta 1,000 feet long. Experimental explosive anchors embedded two of the legs, while a 12,500-pound clump anchor containing a radioisotope thermoelectric generator held the third leg. The entire structure was heavily instrumented in order to collect current profile data and position data.

These data were used to validate the computer program DESADE. It was found that the program is capable of predicting the steady-state response of complex, submerged cable systems if the drag coefficient for the cables and the current regime are properly modeled.

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SEACON II is a major undersea construction experiment whose major goal was the measurement of a complex, three-dimensional cable structure's steady-state response to ocean currents, and the use of these measurements to validate analytical design models. A secondary goal was to provide a demonstration and critical evaluation of recent developments in ocean engineering technology required to site, design, implant, and operate large, fixed subsea cable structures. The SEACON II structure consisted of a delta-shaped module tethered by three mooring legs in 2,900 feet of water. The top of the structure was positioned approximately 500 feet below the surface. The mooring legs were 4,080 feet long, with each arm of the delta 1,000 feet long. Experimental explosive anchors embedded two of the legs, while a 12,500-pound clump anchor containing a radioisotope thermoelectric generator held the third leg. The entire structure was heavily instrumented in order to collect current profile data and position data.

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## CHAPTER 1

### INTRODUCTION

#### OBJECTIVE

The Navy Seafloor Construction Experiment (SEACON) program supports the Navy's requirement for the development and evaluation of technology for constructing undersea installations. It is part of the Deep Ocean Technology (DOT) Project sponsored by the Navy Facilities Engineering Command (NAV-FAC).

SEACON II is the second in a series of major undersea construction experiments managed by the Navy's Civil Engineering Laboratory (CEL). The primary goal of this experiment was the measurement of a complex, three-dimensional cable structure's steady-state response to ocean currents, and the use of these measurements to validate analytical design models. A secondary goal was to provide a demonstration and critical evaluation of recent developments in ocean engineering technology required to site, design, implant, and operate large, fixed subsea cable structures.

#### BACKGROUND

Multimoored cable structures are an efficient means for providing stable platforms for a variety of instruments in the deep ocean. Attempts have been made to install and evaluate the engineering performance of such structures on several occasions over the past decade. Little quantitative structural response data have been obtained. During this same period numerous analytical models have been developed to analyze the steady-state behavior of moored cable systems. These models attempt to predict the tensions in the cables and the geometry of the moorings acted upon by steady-state ocean currents. None of these models yield exact solutions because of the assumptions made regarding structural

properties and hydrodynamic loading criteria and because of the errors inherent in the computational techniques. Because little experimental data exist to validate models, precise validation data are needed to quantify the errors associated with the various techniques [1-1].

#### APPROACH

The SEACON II structure (Figure 1-1) was designed and built primarily to satisfy this need for data on the steady-state response of a complex cable structure to ocean currents. A trimoor configuration was selected to provide a complex, statically indeterminate structure for evaluating comprehensive steady-state analytical models. One of the analytical models was selected for designing the structure and for making predictions of the structure's response to the expected range of currents at the implant site. The structure size and implant depth were selected to provide a challenging implant exercise and to allow reliable extrapolation of the validation data to the size of structure that might be designed for the deepest locations in the ocean. An instrumentation system was designed to meet the structure's predicted response and the level of validation desired.

The structure was built, installed, and maintained in the ocean for 22 months, from August 1974 to May 1976. During the implantment period current profiles and corresponding structure response were measured. The structure was then recovered to permit visual examination of its condition and to perform tests on its components.

This report describes the design of the system and its implantment and performance. The results of the structure's response to ocean currents are presented along with a preliminary analysis of these results relative to analytical predictions.

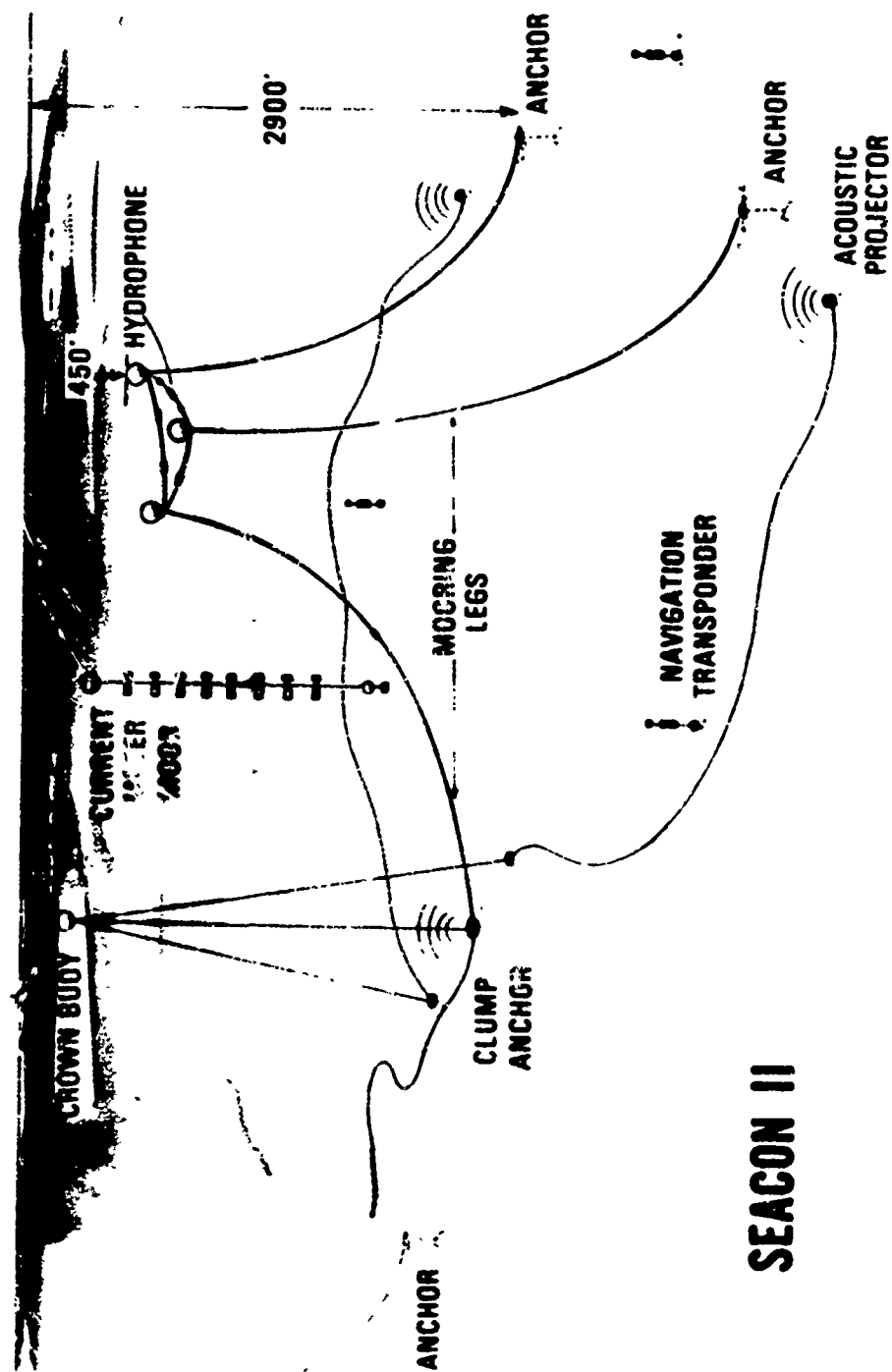


Figure 1-1. Artist's view of implanted SEACON II structure.

## CHAPTER 2

### SITE INVESTIGATION

#### SECTION 1 - SITE CRITERIA

This chapter describes and evaluates the SEACON II site selection and investigation effort conducted by CEL off the coast of Southern California. Prior to conducting any site survey operations, a listing of critical environmental factors [2-1] was consulted, and the following site criteria were established:

- Water depth must be between 2,000 and 6,000 feet to allow for the installation of a large enough structure so that results can be confidently extrapolated to structures in water depths of 15,000 to 20,000 feet. This depth range would also be sufficient to locate the instrumented "delta" below the zone of significant surface effects.
- Ocean currents must be as high as 15 cm/sec a significant period of the time at 500 feet and must reach down to the bottom. Maximum currents at 500 feet and below should not exceed 50 cm/sec. Currents that change significantly in magnitude and direction are a requirement.
- The site must be within 40 miles of Port Hueneme to permit use of CEL's warping tug and diving boats to conduct the sea operations.
- The site must have a relatively large area (2-mile diameter) of nearly constant depth ( $\pm 20$  feet).
- The site must be located outside shipping lanes, submarine lanes, ranges, trawler fishing grounds, or other locations with significant operational constraints.
- The site should have a sea state less than 3 more than 50% of the time year round.
- The site must have at least 50 feet of unconsolidated sediment cover to permit use of deep ocean embedment anchors with sediment flukes.

#### SECTION 2 - SITE SURVEY

##### PRELIMINARY SURVEY

Five potential sites for a preliminary survey operation were chosen from literature search and from U.S. Coast and Geodetic Survey bathymetric charts. The site criteria guidelines described above were applied to the extent possible in selecting the five sites of interest shown in Figure 2-1.

The preliminary site survey operation was conducted from the T-AGOR 13, *USNS Bartlett*, a U.S. Navy oceanographic vessel, from 2 to 8 June 1972. The survey consisted of (1) bottom core sampling, (2) salinity, temperature, and dissolved oxygen profiling, and (3) bottom and subbottom profiling. Current measurements were not made during this cruise due to lack of ship time and equipment.

At the time of this cruise, a 6,000-foot depth for the SEACON II site was favored in order to provide a serious challenge to three-dimensional array construction technology. Sites 1 and 5 in the Santa Cruz and San Clemente Basin, respectively, were the only two 6,000-foot sites initially considered. The San Clemente Basin site did not meet the 40-mile-from-Port-Hueneme range requirement, but it was located near the Navy facility at San Clemente Island which could be used as a base of operations.

In September 1972 CEL and NAVFAC personnel discussed SEACON II objectives and site selection in light of revised project goals. It was decided that collecting performance data for validating analytical models for design of underwater cable arrays would be the primary goal. Array construction technology development was a secondary goal, which reduced the need for the extra cost and risk of going to a depth of 6,000 feet with the experiments if a suitable site at a shallower depth could be found. With this change in emphasis, the three sites with depths ranging from about 2,000 to 3,000 feet—two south of Santa Cruz Island and one in the Santa Monica basin—became serious contenders.

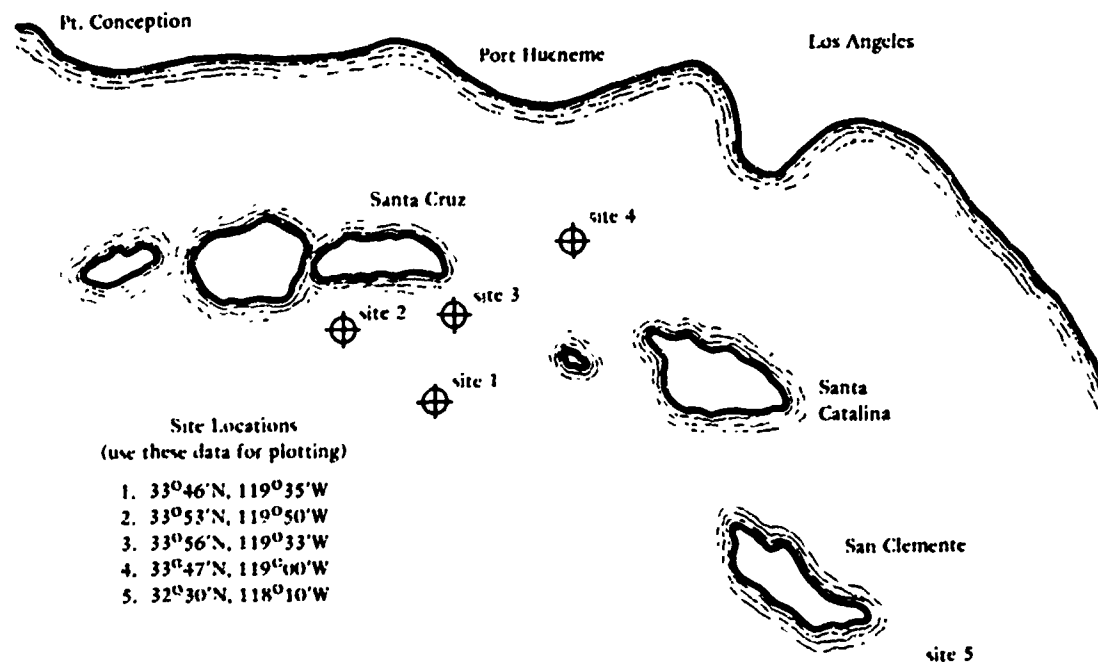


Figure 2-1. Potential SEACON II sites surveyed during 2 to 8 June 1972 cruise.

Data taken at each of these sites were examined with the following results. The profiles from the two Santa Cruz Island locations showed no flat, level site of sufficient size to meet the criteria. However, the Santa Monica Basin had very large, flat, nearly level areas with water depths ranging to 3,000 feet. Another factor which weighed heavily in the decision-making was that both Santa Cruz Island sites were located within the Pacific Missile Range, an undesirable operational constraint. A suitable Santa Monica Basin site, however, could be found just outside the range boundary.

#### DETAILED SURVEY

Despite many favorable factors some uneasiness existed regarding selection of the Santa Monica Basin site. Of greatest concern was that no measured current data, except for surface currents, were found in the literature. Other site criteria could be compromised, but to meet the requirement that the structure be displaced a significant amount, no compromise could be made in the required current

regime. Therefore, determining currents at the site became first priority in the site survey effort.

#### Ocean Currents

Compiling information on ocean currents proceeded simultaneously on two fronts. The ONR Liaison Officer, Monterey, California, was requested to provide CFI with year-round predicted currents at the Santa Monica Basin site. Concurrently, CFI began preparations to make current measurements at the site.

The following information [2-2] was received from the ONR Liaison Officer for the location 33°50'N, 119°00'W in late October 1972

"The permanent current below 200 meter depth is towards the northwest year around. During the summer, the average speed varies between 15 and 18 cm/sec, whereas in the winter the average speed is, in general, less than 10 cm/sec. In this location the permanent current reaches near the bottom, but decreases in the very bottom layers due to friction. The

maximum tidal currents are 9 to 12 cm/sec. The axis of the tidal current ellipse is oriented to 110 degrees to 280 degrees.\*

This prediction indicated the summer currents would certainly be of high enough magnitude and would change sufficiently in magnitude and direction as the tidal currents add and subtract from the permanent current to meet the siting specifications. The data for the winter currents were marginal, however when the permanent and tidal currents were added, the resulting velocity just reached 15 cm/sec.

A current measurement cruise was conducted on 29 to 30 November 1972 aboard the USNS *Bartlett*. The cruise had two phases to it, collection of real time data and implantment of a current meter moor. First, a single-point moor (Figure 2-2) with a current meter and a CCTD (current, conductivity, temperature, and depth) meter was to be installed 500 feet below the surface. This was to be a taut moor with a subsurface buoy and a surface spar buoy. When the deployment was nearly completed, it was found that the moor was about 150 feet too long. Since it would be difficult to recover the moor with the USNS *Bartlett*, it was decided to use the subsurface buoy as a surface float, collect data for 2 or 3 days, and then recover the moor with another vessel before the surface buoy parted or was cut loose.

Unfortunately, foul weather delayed a recovery attempt until 8 days after implant, and, even then, white caps and 5-to-6-foot seas made an organized search pattern impossible. The surface buoy was not located. The next opportunity to search was 2 weeks after implant. After an extensive search effort failed to locate the surface buoy, signals were transmitted to trigger the explosive release; no buoy surfaced. Probably, the buoy sunk or broke loose, resulting in the moor laying on the bottom.

Due to the importance of the data, the Deep Submersible Vehicle (DSV) *Turtle* was engaged from Submersible Development Group One (SUBDEVGRU-1) to search for the moor. On 16 January 1973 DSV *Turtle* dove to the bottom, but deteriorating weather forced her return to the surface without conducting a search. On 9 February 1973 DSV *Turtle* again dove, and this time it conducted a 4-hour search, covering the area shown in Figure 2-3. No moor was located, and the search was abandoned.

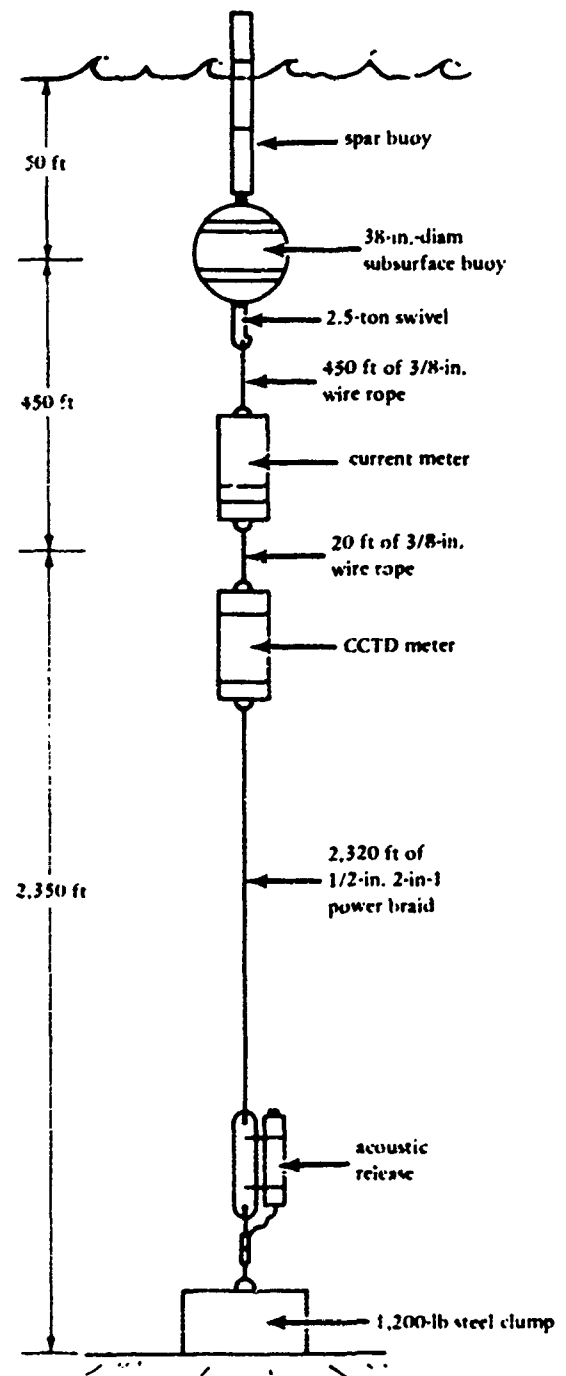


Figure 2-2. Current meter moor for detailed site survey.

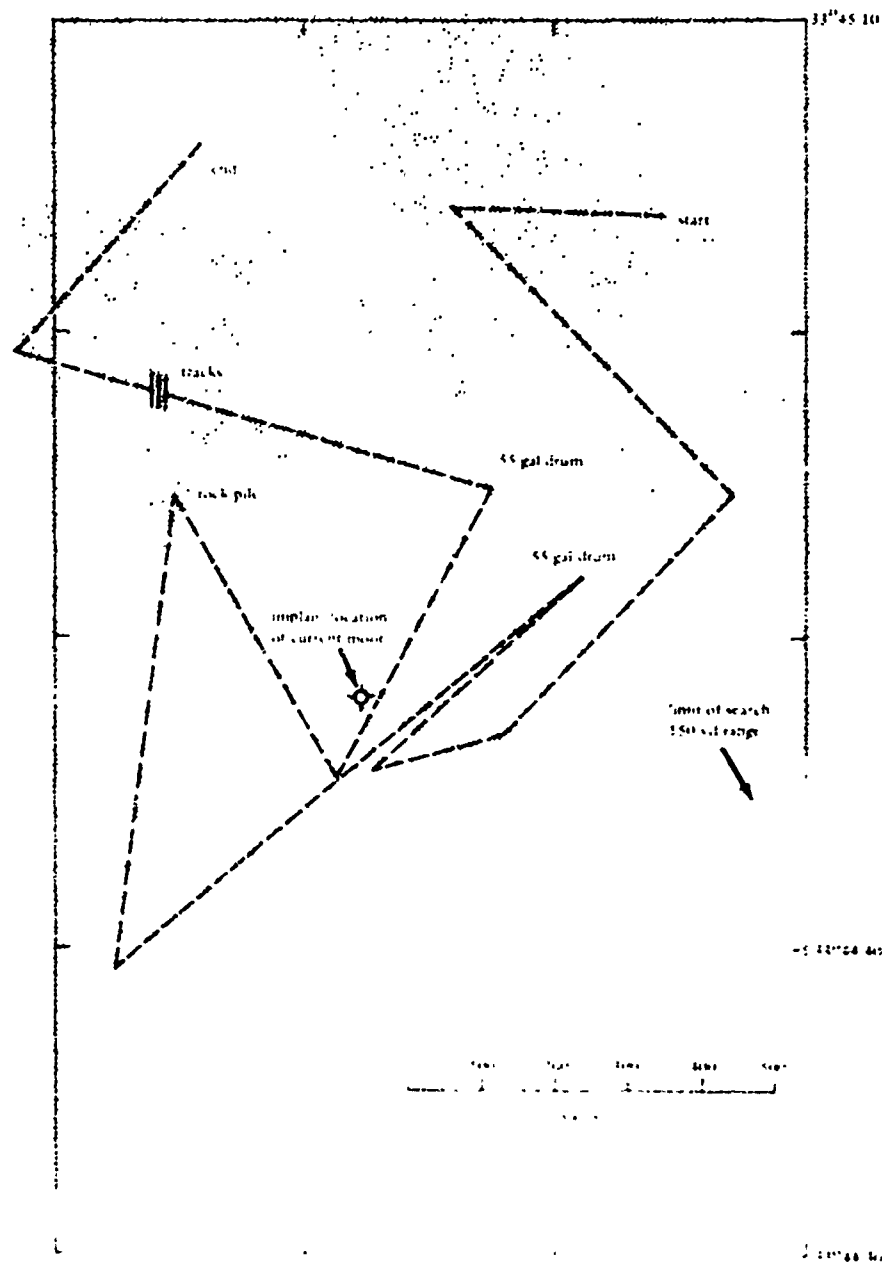


Figure 2.3. Search pattern conducted by manned submersible *Depth* for lost current meter moor



The second phase of this current meter cruise on 29 to 30 November 1972 involved anchoring the *USNS Bartlett* and lowering a self-recording Hydroproducts Model 505 current meter and a Hydroproducts current speed sensor (Figure 2-4) with a deck readout to provide an immediate indication of current profile for the area. During one profiling the currents ranged from a low of about 2 cm/sec to a high of about 15 cm/sec (Figure 2-5). These data were confirmed by the tape on the self-recording meter after it was recovered.

The meager data collected on this first current meter cruise were insufficient to make a final site selection decision. Instead, preparations began for another current meter cruise. This second implant was made on 9 May 1973 with two meters: one at 550 feet, and the other at 1,050 feet in 2,890 feet of water. Figure 2-6 shows the moor configuration. Several significant changes were made in design and procedures from the first moor. Most importantly, backup buoyancy was included so that failure of one buoy would not prevent recovery of the moor. Also, the buoyancy elements were pressure-tested before use. At the start of implant, the acoustic anchor release was lowered with a dummy anchor at the site and tested to insure it operated properly. A final important difference from the first implant was the implant vessel and hardware. The CEL Warring Tug was used, and implant equipment was operated by CEL riggers, which resulted in a smoothly run implant operation.

This second implant was followed by two more that differed only in that four meters were installed on the third moor and three meters on the fourth moor. These moors provided data from 9 May 1973 through 13 September 1973, which covered the period of highest expected currents.

Table 2-1 provides a summary of the four current moor implants. Although modifying the implant techniques after the first implant resulted in a perfect recovery record for the next three moors, the data recovery rate was low; only five of the nine meters installed recorded good quality data. Fortunately, however, data were consistently obtained at approximately 500 feet, where the current would exert the largest drag effect on the structure. Figures 2-7, 2-8, and 2-9 present the current data collected almost continuously from May to September 1973 in the

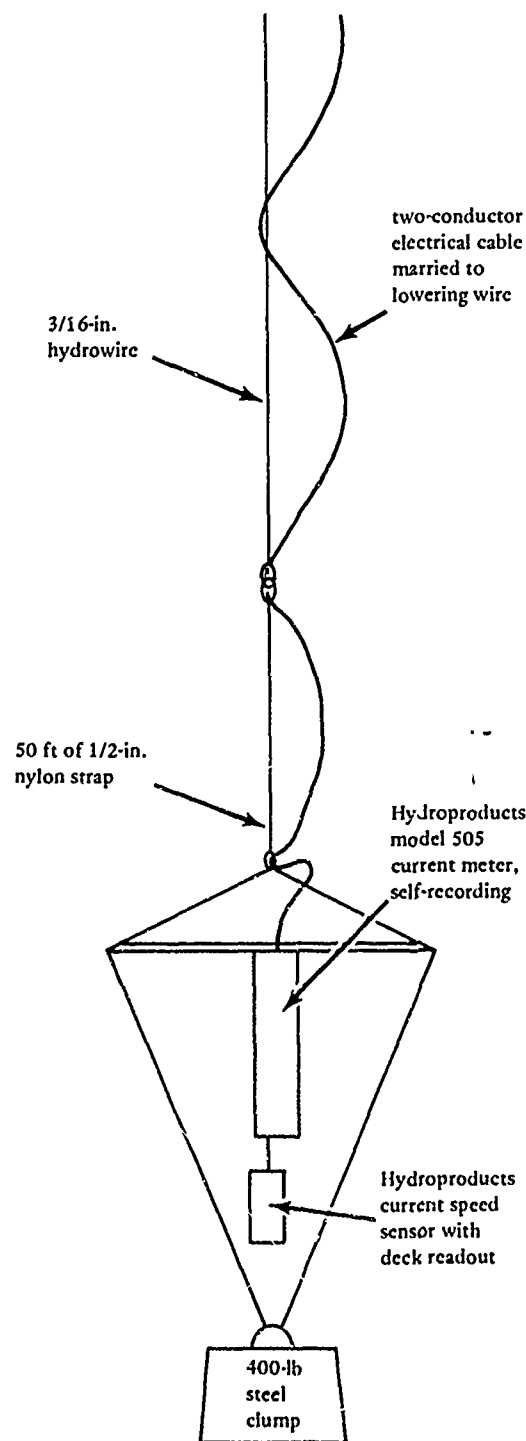


Figure 2-4. Equipment configuration for current profiling.

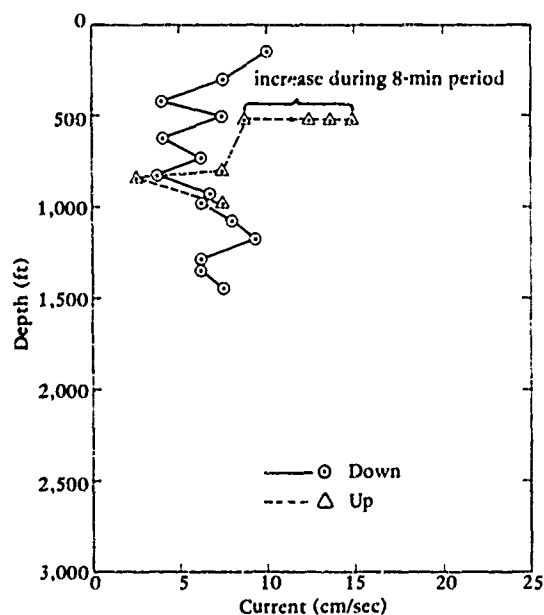


Figure 2-5. Current profiling with direct-reading current velocimeter.

500-foot vicinity. It is evident from the velocity histograms that, as the summer progresses, higher velocity readings are more frequent. In late spring only about 1% of the readings is over 0.3 knot (about 15 cm/sec). By late summer the velocity readings in excess of 0.3 knot are up to about 10%. Note that as more higher currents become more frequent, the predominant direction shifts toward the north. This shift appears to verify at least qualitatively the predicted current data. As the permanent current increases in velocity, its direction, which has a larger northerly component than the tidal current, begins to dominate the resultant direction of the current.

The greatest significance of the data from the site selection and investigation standpoint was that currents in excess of 15 cm/sec were found to occur a significant percentage of the time. The currents, as predicted, reached deeply. Readings taken at 1,050 feet showed the same velocity and direction patterns as those at 500 feet. The currents varied significantly in velocity and direction, decreasing to near zero at times and changing direction often as much as 120 degrees. Based on these results, it was decided that the Santa Monica Basin site provided a suitable current environment for the SEACON II experiment.

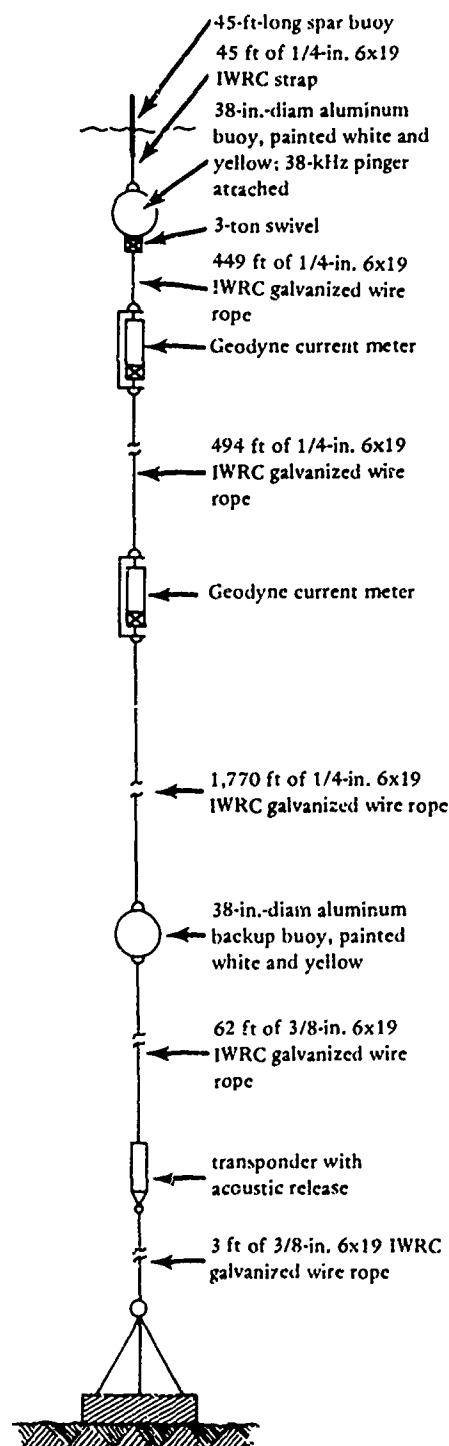


Figure 2-6. Modified moor configuration with backup buoyancy.

Table 2-1. Summary of Current Moor Investigation at SEACON II Site

Moor No.	Location	Date Installed	Date Recovered	No. of Meters	No. of Meters Worked <sup>a</sup>	Remarks
1	33°44'48"N 119°03'18"W	29 Nov 72		2		Moor not recovered.
2	33°44'40"N 119°03'23"W	9 May 73	7 Jun 73	2	2	Routine recovery, good quality data
3	33°44'29"N 119°03'06"W	7 Jun 73	3 Jul 73	4	2	Routine recovery. Two borrowed meters malfunctioned, not discovered until data reduced, so reinstalled
4	33°44'30"N 119°03'30"W	3 Jul 73	13 Sep 73	3	1	Routine recovery same borrowed meters malfunctioned.

<sup>a</sup>45% (5 out of 11) of those meters installed worked.

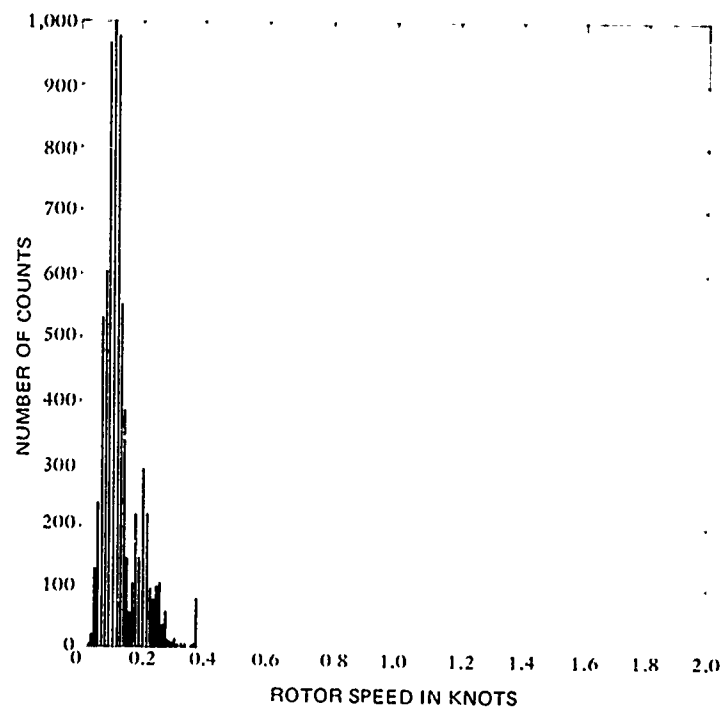
#### Water Column

Water column data were needed to (1) design the acoustic position measuring equipment, (2) reduce the bathometer records for making an accurate topographic chart, (3) derate the batteries, (4) determine the corrosion environment so that the cathodic protection system could be properly designed, (5) determine accurate in-water weights and buoyancies of structural elements, (6) assess the marine fouling environment, and (7) make numerous other determinations. The basic parameters measured were salinity, temperature, and dissolved oxygen versus depth. These properties were essential for determining other parameters such as water density and sound velocity profiles.

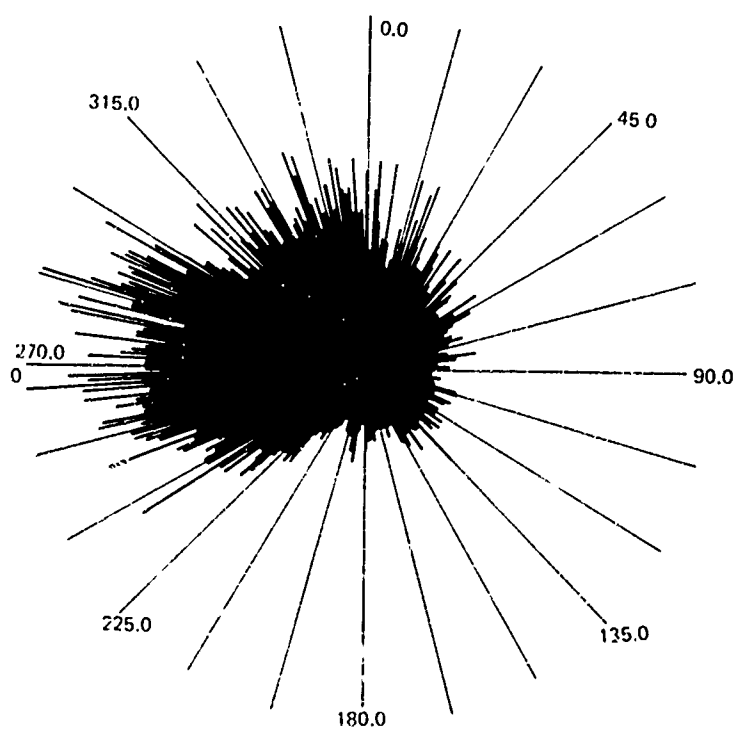
The salinity, temperature, and dissolved oxygen profiles were obtained in the Santa Monica Basin site on 5 June 1972. The profiling system aboard the support vessel, *USNS Bartlett*, was used. Data were recorded on punched paper tape and processed after the cruise at CFI. Figure 2-10 presents the

oceanographic data profiles for the survey location which was about 3 miles northeast of the final SEACON II site. It can be seen that the delta part of the structure, which was designed to be at 450 to 500 feet, is well below the thermocline and the problems it might cause to sound transmission paths. The profiles also indicate that the dissolved oxygen content approaches zero at the basin sill depth of 2,400 feet [2-3], resulting in an anaerobic or near anaerobic condition that must be considered in the mechanical design.

In the process of cross-checking sound velocity measurements made with the SEACON II structure instrumentation, the temperature profile was remeasured more than 3 years after the initial temperature profile data were collected. An expendable bathythermograph was used to collect the data, which are presented and compared with the earlier data in Figure 2-11. Agreement between the two sets of data is quite good except near the surface where the seasonal variation is significant.

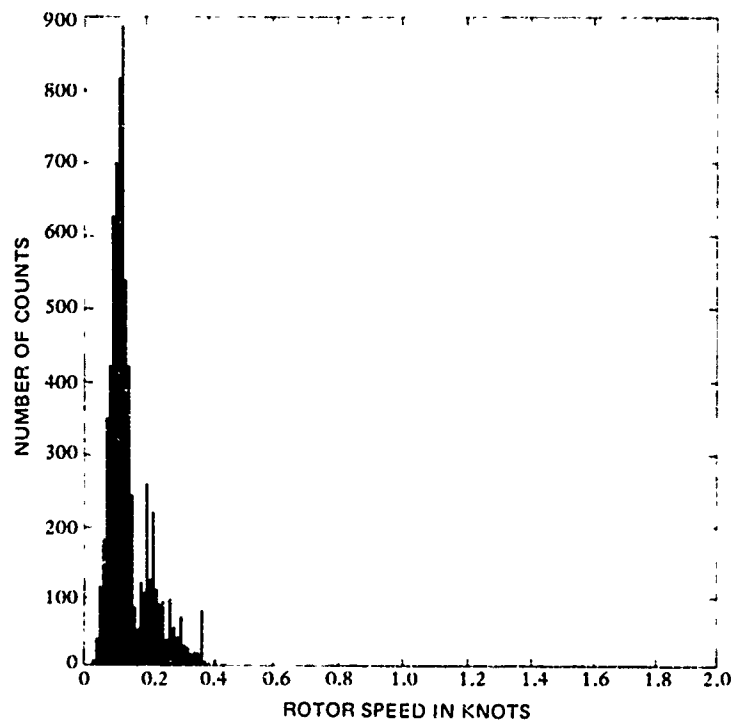


(a) Velocity histogram.

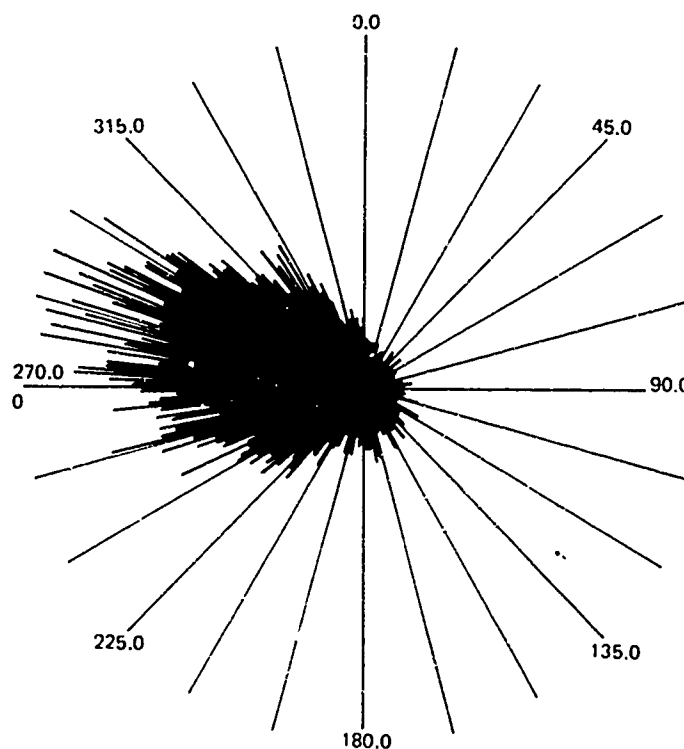


(b) Direction histogram.

Figure 2-7 Current data for moor May to 7 June 1973.

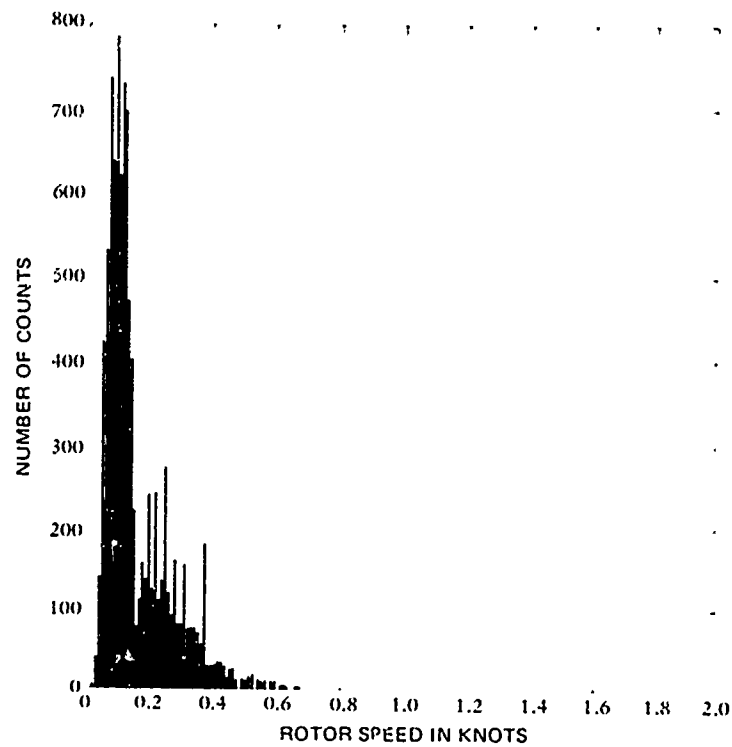


(a) Velocity histogram.

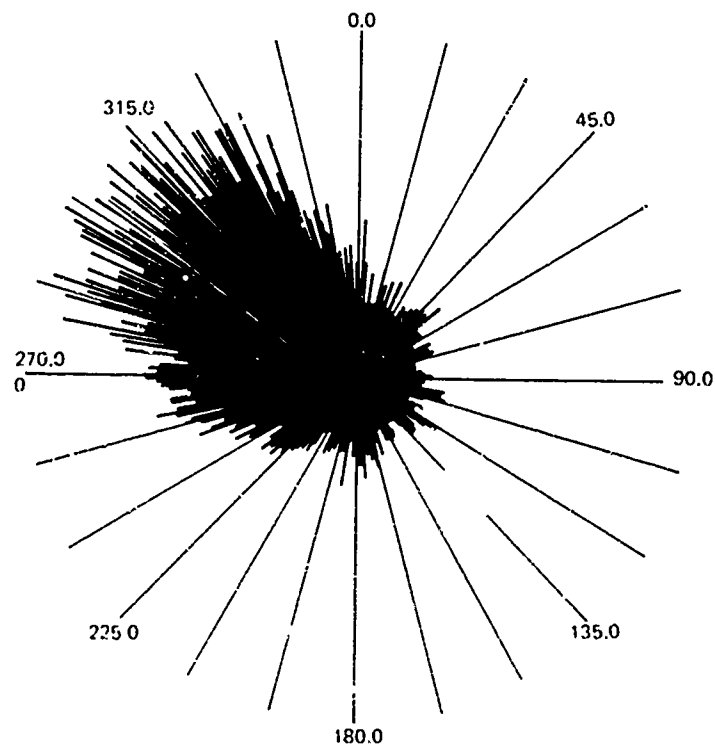


(b) Direction histogram

Figure 2-8. Current data for moor no. 3, 7 June to 3 July 1973.



(a) Velocity histogram.



(b) Direction histogram

Figure 2-9 Current data for moor no. 4 3 July to 13 September 1973

Oxygen (ml/l)	10	8	6	4	2	0
Salinity (0/00)	33.5	33.7	33.9	34.1	34.3	34.5
Temperature (°C)	3	7	11	15	19	23
Sound Velocity (fps)	5,000	4,950	4,900	4,850	4,800	4,750

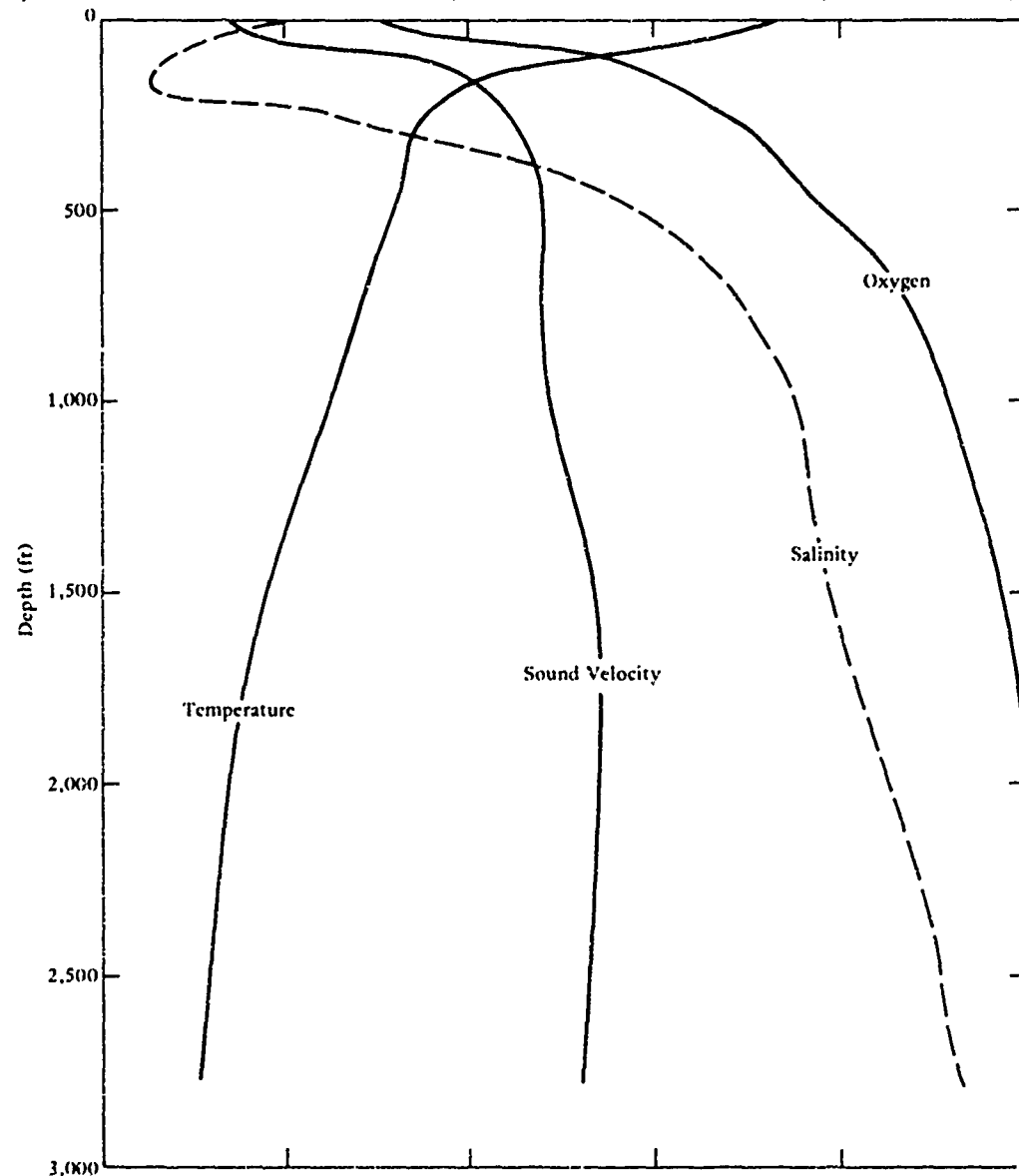


Figure 2-10. Physical oceanographic data profiles at SFACON II site on 5 June 1972

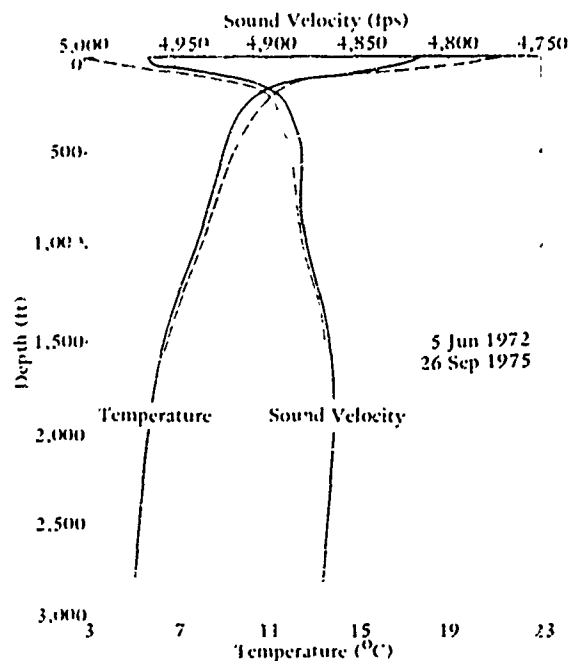


Figure 2-11. Comparison of temperature and sound velocity profiles taken 5 June 1972 and 26 September 1975.

Using the temperature and salinity profiles in the in-situ density of seawater profile,  $\rho_{stp}$  (presented in Figure 2-12) was determined by the Sverdrup's tables [2-4].

An additional piece of data collected on the water column related to transmissibility. The crew of the manned submersible *Triton*, which dove at the site on 9 February 1973, reported visibility was excellent on the bottom; they estimated they could see 50 feet from the sub.

#### Atmospheric and Air/Sea Interface Conditions

Data on surface conditions at the site were available in the literature. Table 2-2 is a summary of the monthly variation of wind, sea, and swell for the site. These data show the requirement could be met for having less than a sea state 3 more than 50% of the time year round. The data also show the summer and fall months provide by far the best weather for conducting sea operations in the site area. This ideal surface weather coincides with the period of highest currents and was selected as the target period for

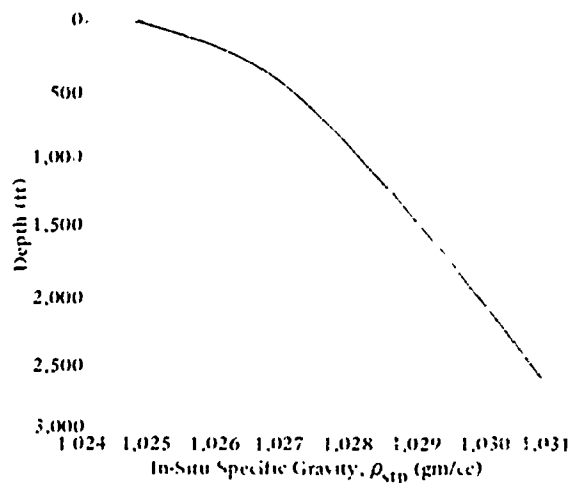


Figure 2-12. In-situ specific gravity profile of seawater at SLACON II site on 8 June 1972.

structure implant and for data taking on the response of the structure to the currents.

#### Seafloor Topography

The bathymetry of the SLACON II site was determined from bottom profiling conducted during the preliminary site survey cruise on 5 to 6 June 1972. Approximately 30 nautical miles of tracklines were run in the site area (Figure 2-13) by the USNS *Battlett* using a 3.5-kHz transducer with Ocean Research Equipment, Inc. Transceiver Model 140. Echo events were recorded on a Raytheon Precision Seismic Recorder, FORAC B, a local radio-navigation net, was used for navigational control, providing positioning accuracy of about  $\pm 50$  feet. The bottom at the site area was found to be nearly featureless with an average slope of 0.2% (25 feet in 12,500 feet) from west to east as depicted in the bathymetric chart in Figure 2-14. This chart is corrected for sound velocity and tide.

Accurate depth data at the proposed location of the dump anchor (A3) was essential to insure the



Table 2-2. Wind, Sea, and Swell Data for SEACON II Site [2-5]

(Data expressed as percent of month.)

Month	Wind		Wave <sup>d</sup>		Swell	
	<6 Knots	11-21 Knots	>2 Feet	>4 Feet	>2 Feet	>6 Feet
Jan	38	25	50	8	60	8
Feb	30	32	55	10	75	18
Mar	28	28	50	13	80	16
Apr	20	28	58	13	75	19
May	30	35	58	15	54	8
Jun	35	30	55	7	58	8
Jul	35	25	45	7	55	8
Aug	35	25	50	5	50	8
Sep	35	30	50	5	50	8
Oct	46	28	43	7	58	10
Nov	38	25	50	8	62	13
Dec	43	25	50	10	63	15

<sup>d</sup>The wave height is the higher of sea or swell for observations containing both wave trains.

crown buoy would be located within proper depth limits (top no shallower than 50 feet, no deeper than 60 feet). Therefore, depth data were collected during current meter implants to cross-check the bathymetric chart data at the same locations. These data all show the bathymetric chart readings to be 3 to 9 feet too deep. A final check at the proposed clamp anchor site was made with a wire sounding. These data indicate the chart reads deep by 3 feet. Data collected during the installation of each anchor indicate the bathymetric chart to be biased on the deep side 4 to 5 feet. However, the relative depths appear to be correct within  $\pm 1$  foot.

#### Sediment Properties and Seafloor Structure

During the preliminary site survey on 5 June 1972 three attempts were made to collect bottom core samples with a hydroplastic corer (3.25 inch ID PVC core barrel, finger retainer, and no piston or

trigger mechanism) at the Santa Monica Basin site. None of these attempts was successful; however, this same corer was used successfully to recover cores at the other sites surveyed. It was surmised that the bottom sediments at the Santa Monica Basin site had little cohesion, probably being composed primarily of silt and sand-sized particles.

To insure embedment anchors could be installed that would develop adequate holding capacity, two anchor tests were performed on 7 February 1973 as described in Chapter 3. Sediment samples were collected from the anchor components after they were retrieved. Grain size analyses were performed on a surface sample from the launch vehicle and from one of the flukes. Based on the Terlineal Oceanic Soil Classification Chart, the results indicate the surface material to be a silty clay, but deeper, where the anchor fluke was embedded, the material was a silty sand.

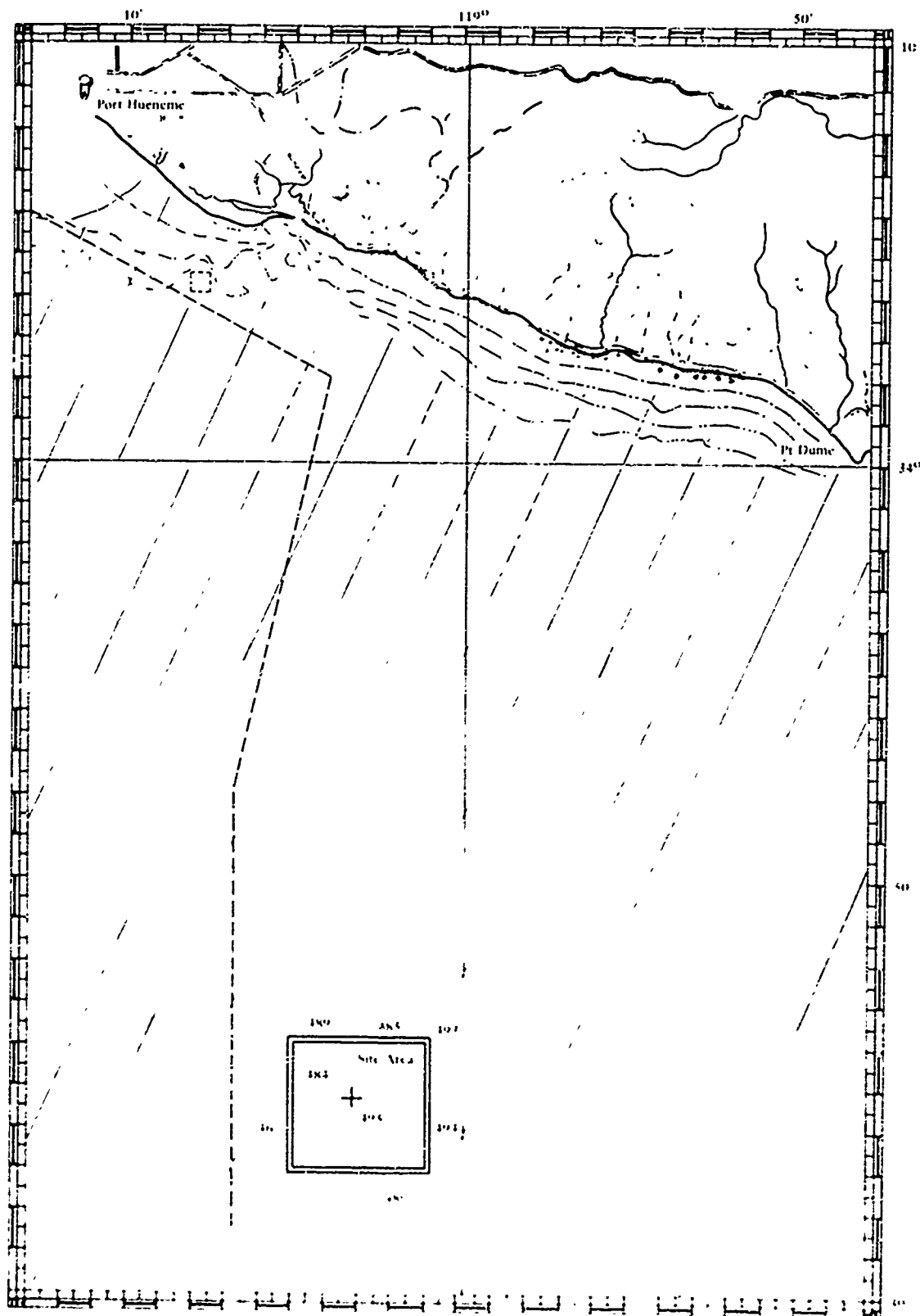
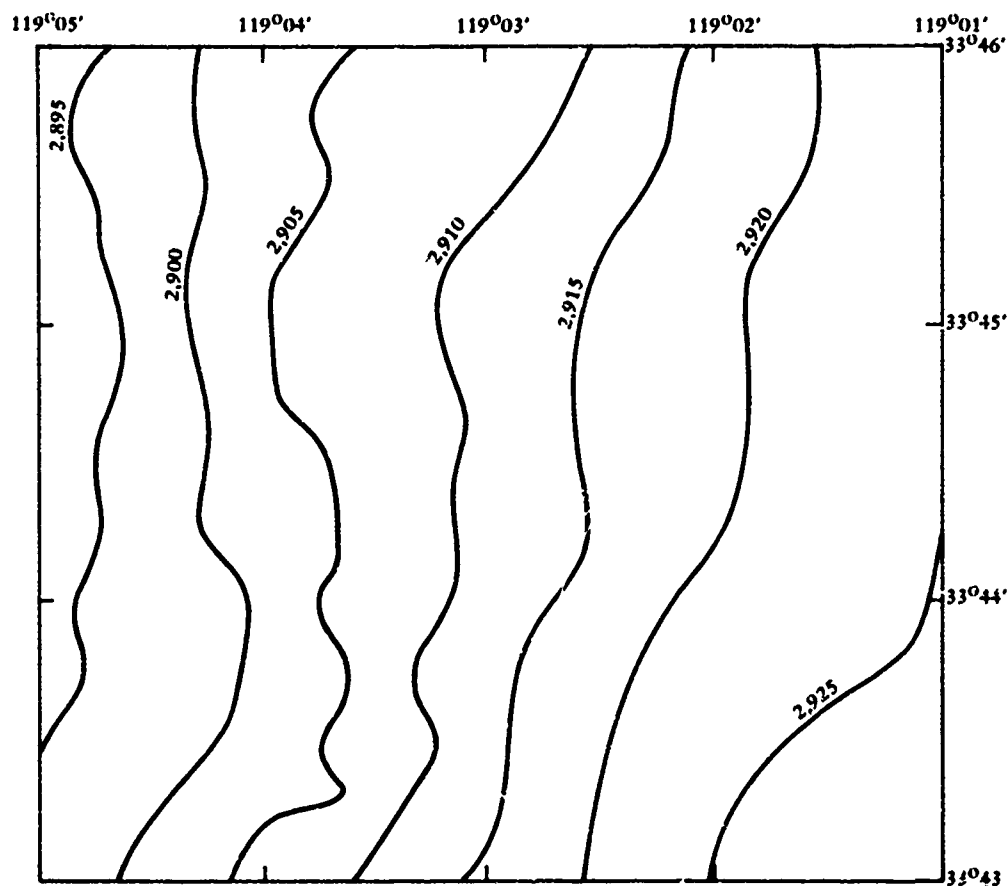


Figure 2-13 SLACON II implantment site area (from C&GS Chart 5202, depths in fathoms)



Depth: feet (corrected to MLLW)  
Contour interval: 5 feet

Figure 2-14. Bathymetric chart of SEACON II site (from CEL survey of 5 to 6 June 1972).

On 9 February 1973 an additional attempt to core the sediments at the site was made with a Benthos Boomerang Corer. A very short sample, only 6 inches long, was retained. Analysis of this core showed the material to be a clayey silt, which corroborates the results obtained from the launch vehicle sample.

No more coring attempts were made because of the previous difficulties in obtaining cores and because the embedment anchors were successfully installed and met design requirements for short-term pullout resistance.

Additional data were obtained on sediment samples collected from the clump anchor, embedment anchor A1, and the embedment anchor at the construction moor during structure retrieval. The

samples from the clump anchor and embedment anchor A1 confirmed the existence of the cohesive layer at the surface and the nearly cohesionless material where the fluke embedded at a depth of 20 to 30 feet. The sediment on the construction moor anchor fluke located approximately 2 miles southwest of all of the other anchor tests showed a different pattern. The material on the fluke was a clayey silt that exhibited considerable cohesiveness. Apparently, significant areal variability exists in the sediment at the location.

Although the total depth of the unconsolidated sediments is not known, the results of 3.5-kHz subbottom profiles indicate bottom-conformable strata exist to a depth of at least 52 feet. Since no deeper echo events were recorded, this measurement

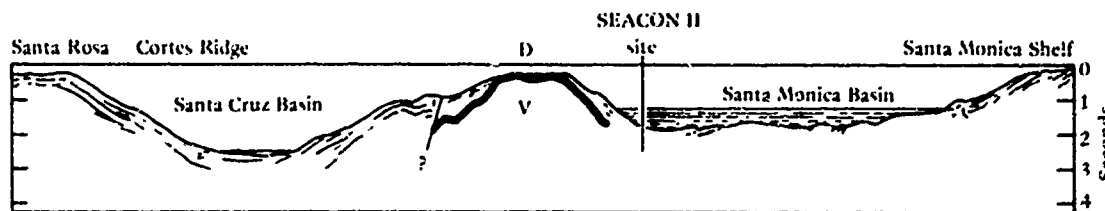


Figure 2-15. Continuous reflection profile for sediment cover existing near SEACON II site.

represents the minimum sediment thickness at the site.

The results of a continuous reflection profiling run near the SEACON II site are shown in Figure 2-15. The bottom-conformable strata are postorogenic sediments, largely of turbidity-current emplacement [2-6], which could explain the significant areal variability found. The round-trip acoustic time for the sediment cover at the closest point on the traverse to the SEACON II site is approximately 0.5 sec. This corresponds to a sediment thickness of about 1,400 feet, assuming a sound velocity of 5,600 fps. This information allayed any concern over inadequate sediment cover for the proper working of the embedment anchors with sediment flukes.

#### Operational Factors

The Santa Monica Basin site is located 27 miles from Port Hueneme, well within the desired limit of 40 miles. The site is 8 miles outside the established shipping lanes, and it is also outside submarine transit lanes and dangerous material dumping areas. The closest boundary of the Pacific Missile Range is about 4 miles away. The area has not been leased for mineral recovery operations, and the site is located in international waters. The National Marine Fisheries Service was contacted [2-7] to investigate possible trawling activities in the area. It was indicated that there is no trawling conducted south of the Ventura County line. However, swordfish harpooning does occur in the site area and could go deep enough to become entangled with the structure. The line used typically has a breaking strength of about 600 pounds, so it would be unlikely any serious damage would be sustained by the structure if entanglement occurred.

#### RESULTS AND DISCUSSION

The lack of data available for conducting an engineering site selection and investigation was quite surprising, especially for a site area adjacent to the Southern California coast. The least amount of information was available for the most critical parameters for an array installation—ocean currents and seafloor sediment properties. The state-of-the-art of measuring equipment, the large areal variability, and the high cost and difficulty of making quality measurements of these two parameters are all factors which help explain the paucity of data. The collection of data on these parameters specifically for the SEACON II project was met with great difficulty.

Good quality sediment cores of adequate length were not collected. This made it necessary to field-test the explosive embedment anchors at the site to insure they would operate properly. A free-fall penetrometer device presently under development by C&I would likely have been a very valuable site investigation tool had it been available. Adequately developed it would have provided penetration data directly applicable to the embedment anchor design without the requirement for cores or anchor field tests.

The measurement of currents in the Santa Monica Basin to determine if the velocity and direction characteristics of the current were suitable for the SEACON II experiment was a frustrating experience. A variety of meters was available in the C&I inventory and on loan. Each had different procedures and equipment necessary for implantment. The recording medium and format varied from meter to meter. The data processing was different for each meter, and none could be reduced in-house. The

result was poor data recovery and a very long time lag (averaging about 2 months) in obtaining reduced data for analysis. Nearly 1 year was required to confirm the current regime met the site selection criteria.

In general, the measured current data appear to agree with the predicted data obtained from a numerical model for tidal effect and a geostrophic flow model for determining permanent current. How much coincidence is involved in this agreement is not known; the site's nearness to the coast and the Channel Islands and its basinal character make anything more than qualitative predictions extremely difficult if not unlikely.

Compared to the effort required to obtain sediment and current data, the remainder of the site investigation effort was routine. The standard techniques used to collect data and process them were adequate, and accuracies were sufficient for engineering purposes. Data on site characteristics obtained from the literature and personal communications proved accurate except in one instance. Although no deep trawling supposedly was done in the site area, as noted in Chapter 3, a piece of trawling net was found entangled with one mooring leg.

The LORAC B navigation net was adequate for site selection when both transmitting and receiving equipment were operating properly and were not being interfered with by skywave effects or ship radio transmission. The equipment is relatively old, however, and subject to frequent breakdowns, which result in either poor position data or time-consuming recalibration runs.

#### FINDINGS AND CONCLUSIONS

1. A site suitable for the implant of the SEACON II structure was successfully located and investigated.
2. Virtually no data were found in the literature on the two most important parameters -- currents and sediment properties -- for implant of an undersea cable structure, such as SEACON II. Apparently, due to lack of adequate equipment and the cost involved, these site data are not generally available even in a well-studied area, such as the southern California coastal waters. The lack of data on currents required a 1-year effort to accumulate sufficient data to make a final site selection decision.

3. Due to coring equipment limitations in the sediments encountered, no suitable core was obtained. This necessitated costly field testing of the embedment anchors to insure they would operate properly at the site. An alternative to coring or more reliable coring techniques are needed.

4. Measured and predicted currents, both velocity and direction, appeared generally to agree.

5. The LORAC B system provided adequate position data for the site investigation when transmitting and receiving equipment were both operating properly; however, frequent breakdowns were experienced.

6. Contrary to site information, deep trawling was conducted in the area at least once because a trawl became entangled with the SEACON II structure.

#### RECOMMENDATIONS

1. The Navy should establish a physical environmental measurement program to obtain environmental data for engineering purposes at numerous locations around the world which are likely to be candidates for undersea construction activities. This would avoid the long lead time involved in site selection. Current regime and sediment properties are the most important parameters to be accumulated in a data bank.
2. The Navy should continue to support the development of a current measurement system for ocean engineering that incorporates ease and reliability in implant and recovery, and has central control and recording, low cost sensors, and low threshold and high accuracy sensors.
3. The Navy should continue development of the expendable free-fall penetrometer as an efficient means of determining engineering properties of sediments without coring. Sufficient tests in many different sediment types should be conducted to "calibrate" the penetrometer for any ocean location. Development should also concentrate on engineering to reduce the unit cost to a reasonable level.
4. The Navy should critically evaluate acoustic means for determining engineering properties of sediments in situ. This technique could provide another alternative to coring or, at least, to extensive coring activities.

5. Studies should be conducted to determine the reliability of ocean current prediction techniques for engineering needs at ocean construction sites.

6. A new ship positioning system that covers generally the present area served by the obsolete LORAC B net should be procured and installed. LORAN C, which should be operational in this area in early 1977, may satisfy at least part of this recommendation.

## CHAPTER 3

### SYSTEM DESIGN AND PERFORMANCE

#### SECTION 1 - DESIGN CONCEPT

##### GENERAL

Since the SEACON II structure was an experimental "tool" rather than an operational system, it permitted greater latitude in selecting a general concept, including shape, configuration, and size. A three-dimensional cable structure with a horizontal delta inclusion was selected to provide a comprehensive test of available analytical models. The configuration chosen appeared to have practical value in providing a very stable subsea structure with the delta being a convenient platform on which to mount instruments. Should a similar structure be built for an operational system the results of the SEACON II experiment could be directly applied with little interpretation or extrapolation.

The approximate size of the structure was initially bracketed to be between 2,000 to 6,000 feet high with the delta sufficiently deep to avoid significant surface effects. It was concluded by Dominguez [3-1] that, if a properly validated numerical model was obtained on the SEACON II structure, the results could be extended to cable structures 8 to 10 times its size. Thus, the data from this size of structure could be applied to the design of a submerged cable structure at virtually any ocean depth. This size range also appeared to be sufficient to extend the state-of-the-art in the implant of such a complex structure, since no trimoor supporting a large platform similar to the SEACON II delta had ever before been installed.

##### STRUCTURE DESCRIPTION

The SEACON II structure (Figure 3-1) consisted of a delta-shaped module tethered by three mooring legs (L1, L2, and L3) in 2,900 feet of water. Legs L1 and L2 were torque-balanced mechanical cables, and

L3 was a torque-balanced electromechanical (EM) cable. Each leg was 4,080 feet long. The delta module, which had 1,000-foot-long EM cable arms, was positioned approximately 500 feet below the surface and was buoyed at each apex by a 5-1/2-foot-diameter spherical node buoy (NB1, NB2, and NB3). The mechanical cable legs (L1 and L2) were anchored with experimental deep ocean explosive embedment anchors (A1 and A2). The EM cable leg (L3) was anchored by a 12,500-pound clump anchor (A3), which contained a 10-watt radioisotope thermoelectric generator (RTG). The anchors were positioned approximately 6,600 feet apart. An EM wire rope crown line (CL) extended from the clump anchor to an 8-foot-diameter crown buoy (CB) 50 feet below the surface.

The electronics and recording equipment were stored within a removable pressure canister in the crown buoy. Hydrophones for position measurement and pressure sensors for measuring depth were located at the three delta apexes, the one-third points of delta arm D13, the midpoint of leg L3, and 500 feet below the surface on the crown line. One hydrophone was to be located at the midspan of arm D23, but, as discussed later, it flooded during implant and was removed. Three acoustic projectors (P1, P2, and P3) were located on the clump anchor and near the other two anchors, respectively. Tension sensors were located at each end of leg L3, each end of delta arm D13, and at the NB3 end of delta arm D23. The Naval Underwater Systems Center (NUSC), New London, Connecticut, supplied a self-contained instrumented span for delta arm D12 to measure the dynamic response of the structure to the environment. Three current meter strings (CM1, CM2, and CM3) with a total of 19 meters surrounded the structure. Three acoustic projectors (T1, T2, and T3), which were part of an acoustic transponder navigation system (ATNAV), were positioned on the seafloor near the structure.

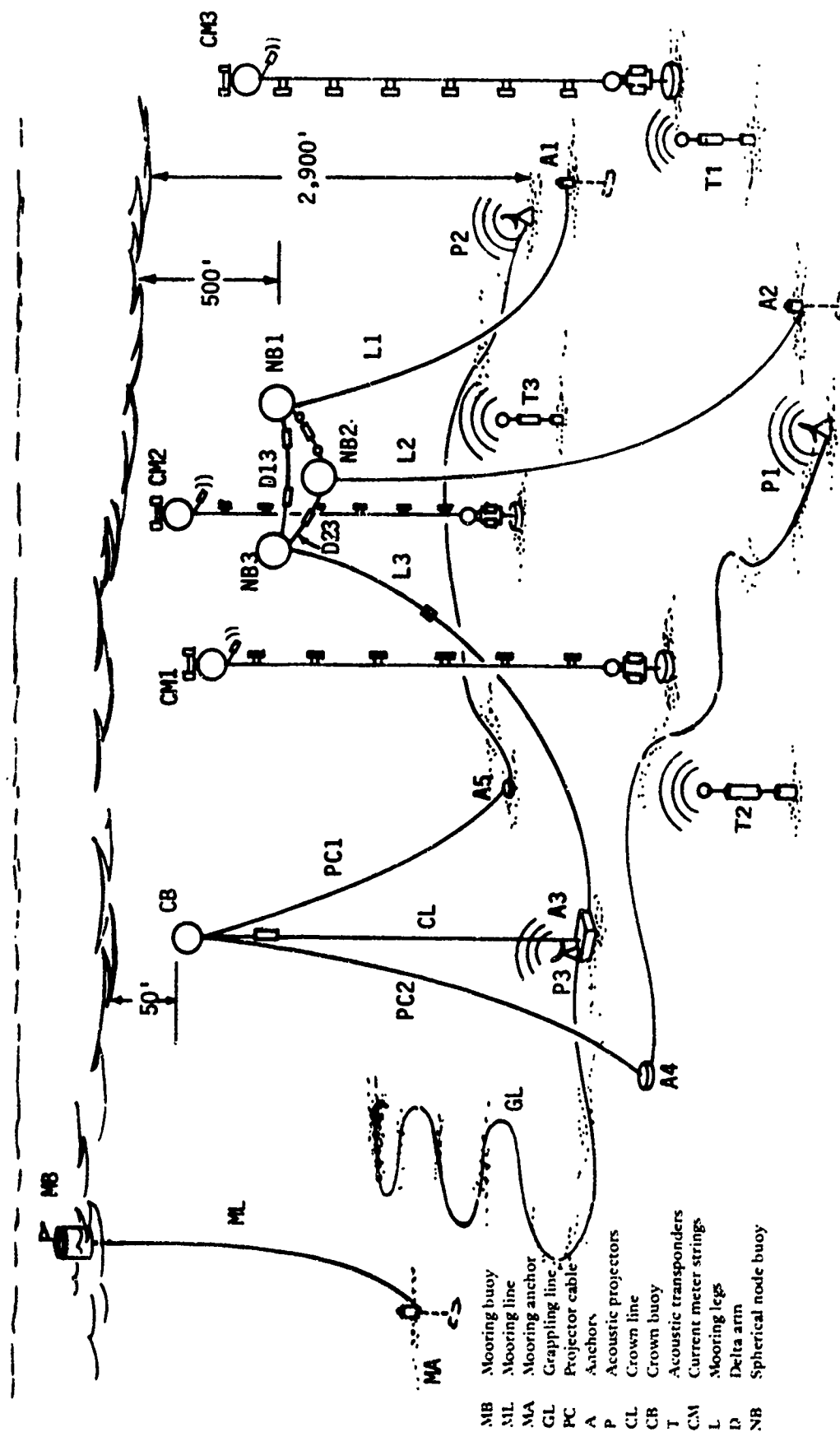


Figure 3-1. SEACON II trimoor structure and associated hardware.



Table 3-1. Summary of Physical Characteristics Used for Design<sup>a</sup>

(Distance between anchors, 6,600 feet.)

Component	Dimensions		Unit Weight (in seawater)	Drag Coefficient	Location
	Length (ft)	Diameter (in.)			
Cables	4,080	0.727	-0.310 lb/ft	1.2 (normal only)	Leg (L1, L2, L3)
Arms	1,000	0.727	-0.310 lb/ft	1.2 (normal only)	Arm (D13, D12, D23)
Node Buoys		67	1,745 lb	0.5	At junctions of arms and legs (NB1, NB2, NB3)

<sup>a</sup>Actual values varied in some cases. Table 3-3 provides data on actual cables used.

#### ANALYTICAL MODELING OF STRUCTURE

The analytical model used to design the SEACON II structure is called DESADE and is described in Chapter 6. DESADE was used to establish the structure design, confirm the suitability of the construction site, and determine the measurement accuracies required to achieve the desired level of validation.

First, various combinations of leg lengths, anchor spacings, and buoyancies were input to the program and analyzed in an iterative fashion. This procedure continued until a preliminary design resulted that had the node buoys at approximately 500 feet below the surface, no cables laying on the bottom, maximum tensions less than 2,000 pounds in all cables except the crown line, and a design compatible with the installation plan being developed concurrently.

Table 3-1 is a summary of the important parameters that resulted from this first stage effort. These characteristics were used as input to the DESADE program along with ocean current profiles to determine the predicted response of the structure to the ocean environment. Using the predictive model the tentative design for the SEACON structure was exposed to two current profiles. A "low profile"

(shown in Figure 3-2) represents the current regime expected 20% of the time at the SEACON site. It was used to determine the minimum node buoy displacement (20 feet from the zero current position of the buoys) and, thus, establish how accurate the equipment used to measure the position of the structure would have to be. The "high profile" (Figure 3-2) was used to insure cable tensions did not exceed those prescribed for the cables. The displacements produced by the current profiles for one assumed direction of flow are shown in Figure 3-2. Note that the "low profile" produced node buoy displacements of 20 feet in the horizontal plane (x-y plane) and vertical displacements of 8 and -14 feet. The "high profile" produced horizontal displacements of approximately 70 feet and vertical displacements of -52 and 21 feet. Under the "high profile," maximum cable tensions were 1,860 pounds in a "leg" and 650 pounds in a horizontal delta "arm." From these data it was determined that adequate displacement of the structure could be expected at the selected SEACON II site.

Since many parameters influence the ultimate level of validation of the analytical model, a parametric study was conducted to determine the

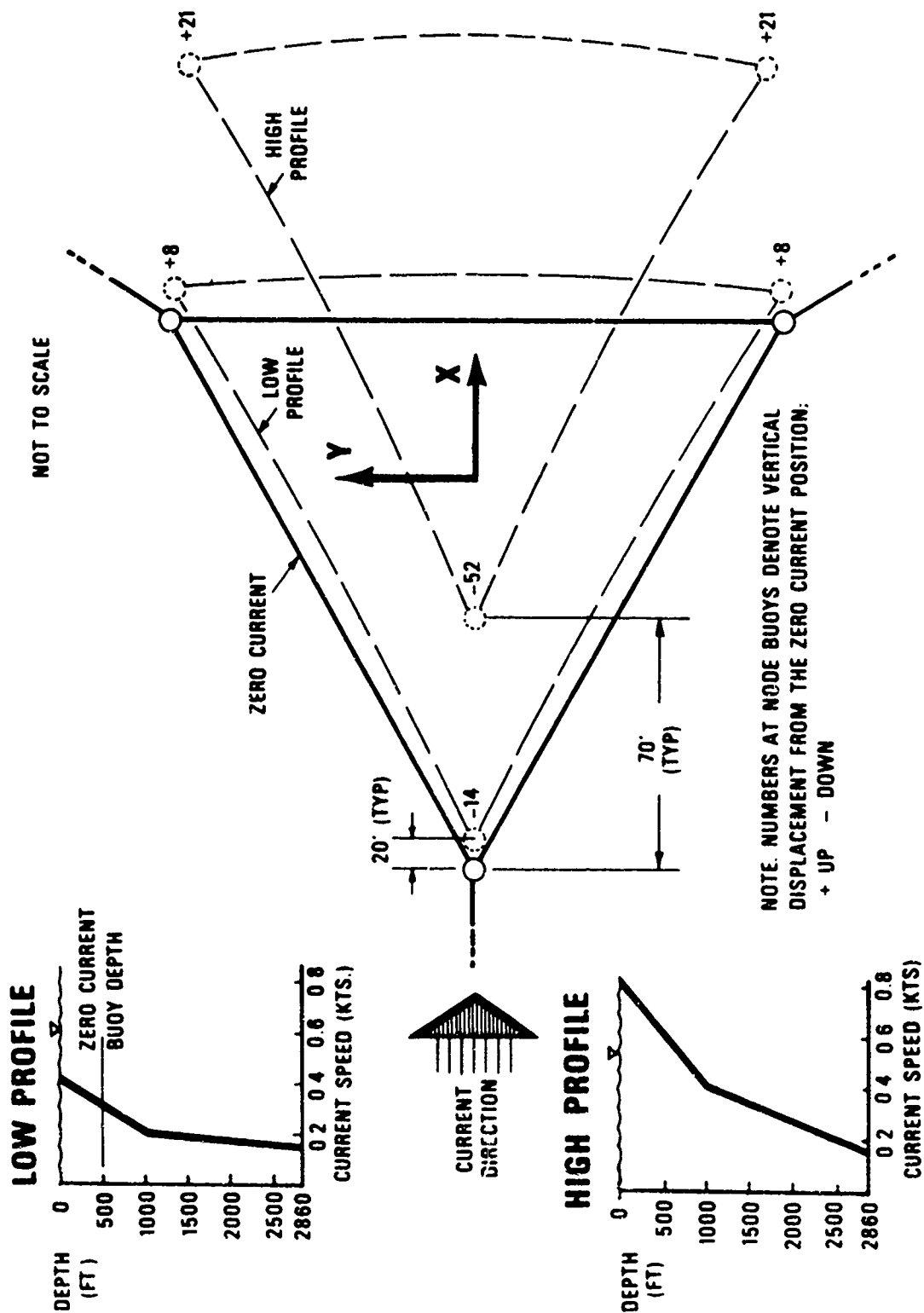


Figure 3-2. Predicted displacement of SEACON II delta under influence of "high" and "low" current profiles.

Table 3-2. Equivalent  $C_d$  Accuracy of SEACON II Parameters

Equivalent $C_d$ Variation <sup>a</sup>	Position Measuring (ft)		Ocean Currents		Cable Diameter (in.)	Fluid Density (slugs/ft <sup>3</sup> )
	x-y	z	Velocity (cm/sec)	Direction (deg)		
±0.25	±13	±11	±2.5	±10	±0.11	±0.33
±0.10	±5	±4.5	±1.0	±4	±0.05	±0.14
±0.05	±2.5	±2.0	±0.5	±2	±0.025	±0.06
±0.02	±0.5	±0.4	±0.1	±0.5	±0.005	±0.03

<sup>a</sup>Variation about assumed normal  $C_d$  equal to 1.2.

impact of each parameter on validation. A study such as this points out potential sources of error, which allows one to determine if any major measurement problems exist and to specify the measurement accuracies needed to meet the experimental goals.

Since the major factor for relating cause (ocean currents acting on the structure) to effect (movement of the structure) is an effective drag coefficient for the structure, the drag coefficient was selected as the pacing parameter.

Table 3-2 shows six of the parameters examined as a function of the pacing parameter, normal drag coefficient,  $C_d$ . Each of these was examined in relation to a  $C_d$  accuracy level of ±0.10, a level estimated as being necessary for a successful validation experiment [3-1].

The average fluid density measurement for the site is accurate to within ±0.003 slugs/ft<sup>3</sup>, this is 50 times more accurate than the fluid density listed in Table 3-2 for an equivalent  $C_d$  accuracy of ±0.10. The average cable diameter measurement is believed accurate to within ±0.003 inch, which is almost 20 times more accurate than the cable diameter for an equivalent  $C_d$  accuracy of ±0.10.

The relative position measuring accuracy of ±5 feet in the vertical and ±4.5 feet in the horizontal posed a serious challenge. To be sure of sufficient accuracy, especially at lower current velocities, a relative position accuracy of ±1 foot was specified for the position measuring system.

The current velocity and direction measurements were a more serious challenge, requiring the design of an elaborate current measurement and calibration system, which is described later in this chapter.

## SECTION 2 – MECHANICAL SUBSYSTEM

### DESIGN GUIDELINES

The major components of the mechanical subsystem include cables, cable terminations and breakouts, anchors, instrumentation housings, and buoyancy elements. Serious wear or corrosion of many of these mechanical components could result in major structural failure, thus, the following guidelines were adhered to in the design of this subsystem.

- The operating lifetime of the mechanical subsystem shall be a minimum of 2 years.
- Critical components shall be designed to meet this minimum 2-year requirement. Critical relates to complete subsystem failure as would result, for example, from the parting of any cable termination.
- Absolute minimum operating lifetime of non-critical components shall be 1 year.

- All wire ropes and wire rope terminations shall be galvanized or aluminized.
- All dissimilar metals shall be electrically isolated or, if isolation is not desired or feasible, the more anodic components shall be much larger than the cathodic components.
- All steel components shall be hot-dip galvanized and/or cathodically protected with sacrificial anodes.
- The radioisotope thermoelectric generator (RTG), its housing, retaining hardware and cables, cable terminations, and connectors associated with it shall all be considered critical items, since it is essential that the generator be safely installed and recovered.
- Materials that corrode uniformly (steel, copper alloys, cupronickels, etc.) are preferable to those that corrode nonuniformly (aluminum and stainless steel).
- Aluminum alloys and stainless steel shall be allowed for noncritical items only.
- Titanium, Inconel 625, and Hastelloy "C" are materials to be used only for critical components that cannot be protected from corrosion damage by other means.

## CABLE AND CABLE TERMINATIONS

### Design Criteria

The major criteria for the selection of cable and termination hardware were: the combination must (1) supply both reliable electrical power and data transmission to and from the structure, (2) have good handling characteristics for implant, (3) withstand the mechanical stresses expected, and (4) survive a minimum of 2 years in the ocean environment. Specific cable criteria are

- All structure cables must be torque-balanced within the present state-of-the-art.
- All electromechanical cables must have a center strength member with a minimum of three electrical conductors (AWG no. 22 or larger)

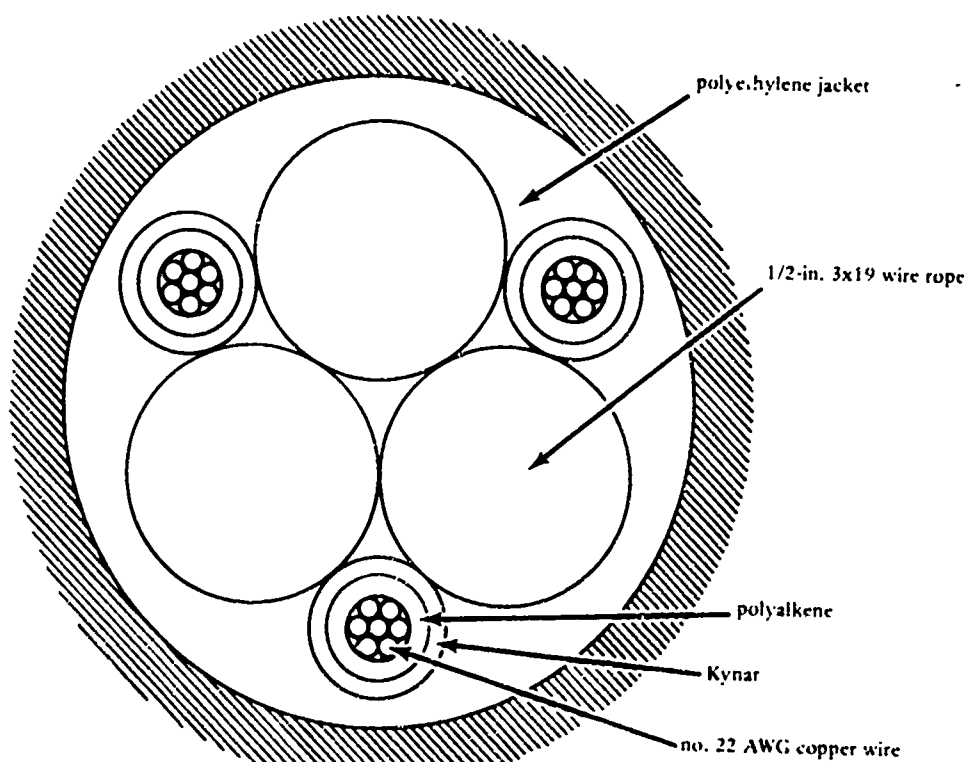
exterior to the strength member, with the exception of the crown line cable which must have a minimum of six electrical conductors with three exterior to the strength member.

- All cables must be jacketed with a smooth exterior covering that can withstand abrasion.
- All cables must be compatible with state-of-the-art terminations.
- All cables must be galvanized or aluminized for corrosion protection.
- All cable terminations must withstand loads up to and including the parting of the cable.
- All cable terminations must be galvanized.
- All cable terminations must be designed so that all electrical conductors can be passed continuously through the termination.

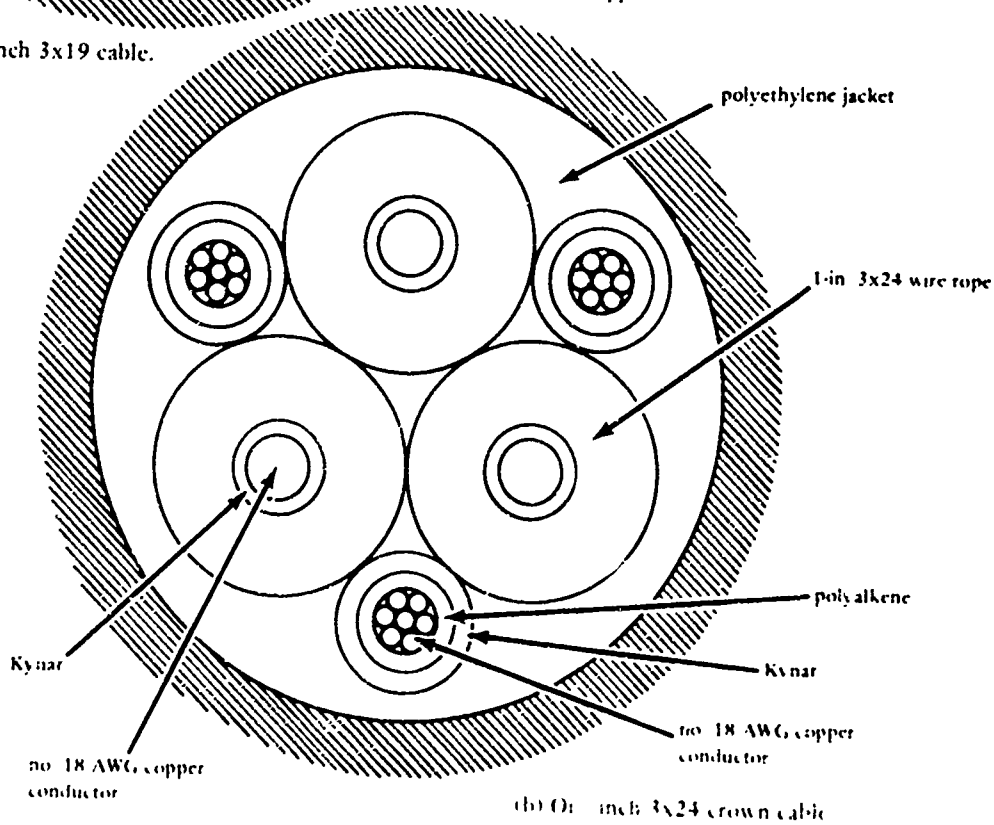
### Cable Description

The basic cable type selected for the SEACON II structure was of three-strand mechanical construction. CEL and other organizations that have had experience with this type of cable have found it to have excellent mechanical properties. It is especially convenient to handle since it is designed to be torque-balanced. NUSC, New London, working in conjunction with NAVFAC and U.S. Steel Corp, New Haven, converted this excellent mechanical cable to an electromechanical (E.M) cable by placing three jacketed no. 22 AWG electrical conductors in the valleys formed by the three strands (Figure 3-3a) and then jacketing the entire cable to hold the electrical conductors in place and to protect them from abrasion. To increase the number of electrical conductors from three to six the center wire of each strand was replaced with an electrical conductor (Figure 3-3b). This configuration was selected for the SEACON II crown line (CL).

At the time CEL tentatively selected this cable for the SEACON II structure only preliminary testing had been completed on the E.M version of it and no work had been done on terminations or breakouts. The cable appeared so promising, however, that CEL decided to tentatively select it and perform the development and testing necessary to assure its reliability for use in the SEACON II structure.



(a) One-half-inch 3x19 cable.



(b) One-inch 3x24 crown cable

Figure 3-3 Cross sections of electromechanical cables

Table 3-3. Physical Characteristics of SEACON II Structure Cable

Structure Member	Nominal Size (in.)	Strength Member Construction	Outside Diameter (in.)	Breaking Strength (lb)	In-Water Weight (lb/ft)	Electrical Conductors		Length (ft)
						Number	Size (AWG)	
Legs (L1 and L2)	1/2	3x19	0.705 <sup>a</sup> and 0.714	25,700	0.320	—	—	4,080
Leg (L3)	1/2	3x19	0.706 <sup>a</sup>	25,700	0.331	3	22	4,150
Delta arms (D13 and D23)	1/2	3x19	0.715 <sup>a</sup> and 0.712	25,700	0.333	3	22	1,001
Delta arm (D12) <sup>b</sup>	1/2	double-armored	0.625 <sup>a</sup>	16,000	0.213	16	20	1,000
Crown line (CL)	1	3x24	1.245 <sup>a</sup>	103,000	1.4	6	18	2,829
Grapnel line (GL)	1-1/8	3x19	1.26	124,000	1.7	—	—	3,500
Construction mooring line (ML)	3/4	3x19	0.75	58,000	0.77	—	—	4,000
Projector cables (PC1 and PC2)	3/16	double-armored	0.182	2,700	0.045	3	24	10,000

<sup>a</sup>Diameter includes jacket.

<sup>b</sup>Supplied by NUSC.

Table 3-3 lists the characteristics of all the SEACON II structure cables. All of the legs, the delta arms, and the crown line were externally jacketed with high-density polyethylene so that the entire structure would be uniform whether the cables were EM or mechanical only. This jacketing added complexities to the cable termination design and corrosion evaluation as discussed later.

The EM leg, delta arms, and crown line electrical conductors were insulated with a cross-linked polyalkene primary and a cross-linked poly(vinylidene fluoride) (Kynar) jacket. The projector cable's three electrical conductors were jacketed with polypropylene.

#### Termination Descriptions

All cable terminations used on the SEACON II structure were DYNA-GRIPs purchased from Preformed Line Products Company. This termination type uses a helical gripping and armoring technique. The gripping forces are distributed uniformly along the cable rather than being concentrated at the end of the fitting. The helical rods are formed such that the inside of the helix is smaller than the outside diameter of the cable; this provides a gripping action when properly installed on the cable.

The majority of the DYNA-GRIP terminations were fitted with articulating ball joints (Figure 3-4) to reduce cable fatigue and the ambient noise generated by the structure. The exceptions were at anchor A1, anchor A2, and the crown buoy; at these points the DYNA-GRIP terminated in clevises.

The sockets of the ball joints were lined with Rulon, a material similar to nylon, to reduce friction and noise that might be generated at these connection points. The electrical conductors passed through a hole in the center of the joint.

#### Testing

All cable and termination testing was done at three locations: U.S. Steel Corporation, New Haven, Connecticut; Preformed Line Products, Cleveland, Ohio; and Civil Engineering Laboratory, Port Hueneme, California.

Both mechanical and electrical tests were performed on the cables. The electrical tests consisted of



Figure 3-4. Typical ball joint connection on DYNA-GRIP termination. Light fouling present after structure recovery.

insulation resistance, attenuation at 14.5 kHz, capacitance, and inductance measurements. The mechanical tests were rotation, breaking strength, and a bending life test of electrical conductors using a 24-inch sheave with the cable loaded at 20% of stated breaking strength.

As noted earlier all cable terminations were DYNA-GRIP. The state-of-the-art for these terminations with unjacketed mechanical cables was such that testing was unnecessary. However, testing was performed by Preformed Line Products Company on the 1/2-inch 3x19 jacketed EM cable terminated with DYNA-GRIPs. The test report shows the DYNA-GRIP termination to be able to develop the full-stated breaking strength of the cable without damage to the electrical conductors.

#### Results and Discussion

The most significant problem detected during the cable tests was electrical shorts to ground in the 1/2-inch 3x19 EM cable. Three test specimens were

provided by the manufacturer for pressure tests at CEL. Two of the samples were 100 feet long, and the third was 40 inches long. All had electrical conductors with polypropylene insulation rather than the polyalkene that was used in the final cable.

The first test was conducted on one of the 100-foot cables coiled so that it would fit in an 18-inch-diameter pressure vessel. Before the cable was submerged in the seawater, its resistance, capacitance, and inductance were measured. All conductors checked out satisfactorily.

The pressure was raised to 150 psi, and conductor no. 1 showed a short to the pressure vessel case. The other two conductors had resistance to ground greater than 50 M $\Omega$ . At 500 psi conductor no. 2 showed a resistance of 100 k $\Omega$  to the pressure vessel, and conductor no. 1 remained shorted. The resistance to ground remained greater than 50 M $\Omega$  for conductor no. 3. Since the cable was considered failed, the pressure was removed. The short in conductor no. 1 disappeared when the cable was removed from the tank, but the 100-k $\Omega$  resistance to ground for conductor no. 2 remained unchanged.

It was suspected that the cable may have been damaged when it was coiled so tightly to fit in the 18-inch pressure vessel. Therefore, the second 100-foot section along with the 40-inch piece were left in their shipping container, and the entire container was placed in the 72-inch-diameter pressure vessel. Before going into the vessel, all conductors except no. 2 in the 40-inch cable had resistance to ground greater than 5 M $\Omega$  at 1,000 volts DC; the no. 2 conductor was received from the factory in a shorted condition.

After the cables were placed in the 72-inch vessel and the head secured, which took about 45 minutes, the conductors were tested for shorts again before applying pressure. Conductor no. 1 of the 100-foot cable and conductors no. 1 and 2 of the 40-inch cable were shorted. Both cables were considered failed, so no pressure was applied. Instead, they were removed from the vessel and thoroughly inspected to determine the locations and probable causes of the failures.

The jacket of the 40-inch sample, which was a test fixture for an electrical breakout scheme, was removed, and the electrical breakouts were inspected. The splice to the no. 1 conductor was lifted, and

Teflon insulation was placed between the steel wire and the splice. The resistance to ground immediately increased to greater than 50 M $\Omega$ . The same procedure was followed for conductor no. 2 with the same results. Analysis of the splices showed there were cracks at the junction area where the pigtail was attached to the main conductor. The unsatisfactory splice had been made by wrapping the wires first with a polypropylene tape and then with a polyethylene tape; then they were irradiated.

The 100-foot specimen was halved until a short section with the failure was isolated. The jacket was then removed, and the conductor was examined under a microscope. A hole was found in the insulation. It was decided that the most probable cause of failure was that, during the process of extruding the jacket over the cable, the polypropylene insulation on the electrical conductor was softened, and mechanical abrasion at this stage broke through the insulation.

Based on this information the manufacturer recommended the polypropylene-covered electrical conductors be replaced with a cross-linked polyalkene primary insulation and a cross-linked poly(vinylidene fluoride) (Kynar) jacket. This insulation was designed to withstand 600°F to 700°F annealing temperatures.

It was later determined that softening of the insulation during the jacketing process probably was not the cause of failure. The cable was manufactured and the conductors laid in the cable at one plant. The cable was then shipped to another plant in a different city for extrusion of the outer jacket. During this process the cable was reeled with wooden blocks inserted to separate the layers and protect the electrical conductors. Instead the wooden blocks gouged the conductors, causing the failure.

To insure the EM cables delivered for use in the SEACON II structure had no faults in the electrical conductors, the voids between the jacket and the wire were backfilled with freshwater and then tested while under pressure (Figure 3-5). No faults were detected in any of the EM cables delivered from the manufacturer. Freshwater backfilling was done for several reasons. The inner voids of the cables were filled with water to prevent a large pressure differential from developing across the jacket wall during pressurization that could damage the cable. Also, freshwater



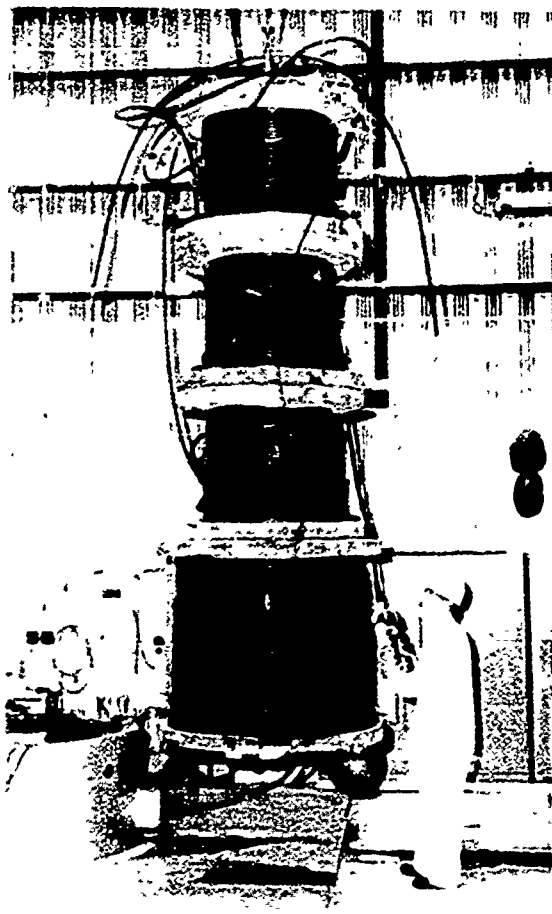


Figure 3-5. Testing EM cables for electrical faults in CEL's 6-foot-diameter pressure vessel.

was recommended by CEL's corrosion consultant to lessen the corrosion rate. Finally, by filling the voids with water and then pressurizing the fluid one was able to obtain highly accurate in-water weights for the cable sections.

The only other potential problem discovered during the cable testing related to the rotational properties of the 3x19 cables. The manufacturer stated an approximate linear increase from 0 degrees per foot rotation at 0 load to about 1 degree per foot rotation at 70% of breaking strength. The Navy Research Laboratory performed tests [3-2] that indicated a rotation of about 5 degrees per foot at about 5% of breaking strength, increasing to about 6

degrees at 70% of breaking strength. This appears to indicate some residual rotation from the manufacturing process was in the cable specimen tested. The difference in results could be due to different testing techniques and to different cable lengths and runs of cable tested. Even at the higher rotation value this 3x19 cable is still one of the most nearly torque-balanced wire rope cables on the market.

Mechanically, the 3x19 and 3x24 cables performed very well. Some of the cables were deployed from a reel through a traction unit, and others were figure-eighted in boxes and deployed by hand. No problems of twisting occurred with any of the cables during loading, payout, or recovery of the structure. The only cable damage was found during structure recovery. It consisted of a small kink at the top of leg L1 and a longitudinal ripping of the polyethylene jacket nearly the full length of L1. It is believed this damage was caused by a deep trawl becoming entangled with leg L1. In fact a piece of trawling net was found still snagged at the top of leg L1 when the structure was recovered.

The electrical conductors in the 3x19 and 3x24 EM cables remained in excellent condition with no shorts for at least 1-1/2 years and probably for the full 22-month implant. A short did occur somewhere in the structure 1-1/2 years after implant during a series of dynamic perturbation tests. However, it is believed this short occurred at one of the termination points and not in any of the EM cables.

The mechanical DYNA-GRIP terminations performed satisfactorily. No slippage between the cable and termination occurred under load, and no damage was done to any of the electrical conductors by the terminations. A potential problem with the ends of the DYNA-GRIP digging into the cable jacket, which could have damaged the electrical conductors, was avoided by placing a protective flared shield between the cable and the end of the DYNA-GRIP.

#### Findings and Conclusions

1. The 3x19 and 3x24 torque-balanced wire ropes used to construct the SEACON II structure performed well structurally and were convenient to deploy and recover, both from a winch stowage unit and figure-eighted in a box.

2. No electrical faults developed in the 3x19 and 3x24 EM cables during the 22-month implant.

3. The DYNA-GRIP terminations performed satisfactorily without any slippage occurring between the terminations and the cables and without damaging the cables or electrical conductors.

#### Recommendations

1. The 3x19 mechanical or EM cables and the 3x24 EM cable are recommended as excellent torque-balanced cables for use in ocean engineering applications.

2. EM cables to be used in ocean construction should be backfilled with freshwater to fill all voids and to reduce the corrosion rate, and they should be pressurized to permit any electrical faults in the cable to be detected.

3. The DYNA-GRIP terminations are recommended as an excellent termination method for mechanical or EM cables. Testing of the specific termination size specified for the cable to be used is recommended to insure proper performance.

#### ELECTRICAL BREAKOUTS AND ELECTRICAL TERMINATIONS

##### Design Criteria

The design of the electrical breakouts and terminations addressed two basic areas:

- The termination of the electrical conductors as they exit the bitter end of the electromechanical (EM) cables.
- The in-line splicing at all locations on the EM cables where there are to be instrument stations.

The design criteria were straightforward:

- The technique must be capable of rendering conductors with a cross-linked polyalkene (polyethylene) primary insulation and a cross-linked poly(vinylidene fluoride) (Kynar) jacket

waterproof to pressures of 3,000 psi and temperatures to 0°C.

- The technique must be able to be done at sea in a relatively short period of time and with no special equipment.
- The splices must survive in the ocean at depths to 3,000 feet for a minimum of 2 years.

#### Splicing Materials and Techniques

**Epoxy Resin.** There were several epoxy resins tried. Both the one- and two-part epoxies were unsuccessful in bonding to the polyethylene. This approach was discarded early in the project and will not be discussed further.

**Hot-Melt Adhesives.** A second method involved use of a hot-melt adhesive. The manufacturer of the hot-melt material is USM Chemical Company, Bostik Division, and the trade name is Thermogrip Adhesive No. 4315. This sealant was recommended because of its application for sealing polyethylene-coated boxes.

The technique for using the hot-melt adhesive involves first removing the Kynar coating from the electrical conductors, leaving only the polyethylene insulation. The Thermogrip material is melted and poured into a mold covering the electrical splice. When cold, the mold is removed, and the hot-melt material is rigid (see Figure 3-6).

**Dielectric Sealing Rubber.** The third technique tried used a dielectric sealing rubber manufactured by AMP Products. This dielectric rubber has the characteristic of remaining malleable at temperatures from 0°C to 250°C.

Before applying the AMP rubber, the Kynar is removed from the conductor to be terminated, and the surface is cleaned. The dielectric sealing rubber is then formed around the splice or termination area, and a protective coating or covering is put over the rubber to keep it in place. The coverings tried included vinyl tape and heat-shrinkable tubing. The heat-shrinkable tubing worked well, because the AMP rubber was not adversely affected by the heat, and, when the tubing shrunk, it forced the rubber into any remaining voids in the conductor splice areas. Figure 3-7 shows several completed tee splices.



Figure 3-6. Tee splice made with hot-melt adhesive material.

#### Testing Procedures

Testing was conducted to determine the most reliable and convenient method of splicing and terminating a cross-linked polyethylene-insulated conductor. The two basic splice types tested were a straight splice where two single conductors are connected and a tee splice where three conductors are joined.

The testing procedures were the same for all splicing and termination techniques and consisted of electrical insulation to ground measurements at varying pressures, temperatures, and voltages. All tests were conducted in the CEL pressure vessel facility.

The testing pressure ranged from 0 to 3,000 psi and the temperature from 0°C to 18°C; the test voltage was 1,600 volts DC or 1,000 volts AC. A sample was considered failed if the insulation resistance fell below 250 MΩ.

Test specimens were made using both the Thermogrip hot-melt material and the AMP dielectric rubber sealant. In preparing the specimens the polyethylene-insulated conductors were spliced to

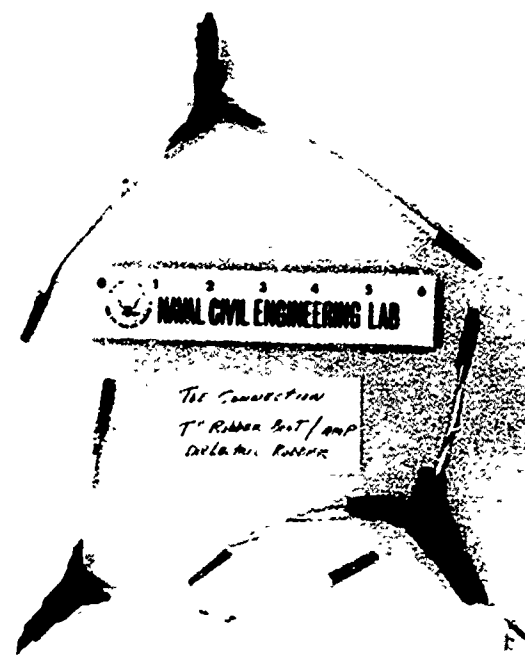


Figure 3-7. Tee splices made with dielectric sealing rubber.

neoprene-insulated pigtailed terminated in single-pin underwater electrical connectors. These were connected to penetrators in the pressure vessel head to permit one to monitor the performance of the specimens while under pressure.

#### Results and Discussion

The hot-melt method was found to be erratic in performance. It was also more difficult and time-consuming to use than the AMP rubber; therefore, it was discarded in favor of concentrating on AMP rubber splice development. However, it was also found to be fairly difficult and time-consuming to make reliable tee splices. Therefore, it was decided to purchase premolded tee splices off-the-shelf and to use the developmental splice technique only for straight splices.

The AMP splices were tested over a 6-month period. During that time less than 2% of the straight splices failed. These splices were made under varying conditions from at-sea to in the laboratory. Minor variations were made on the splice technique, mainly with the shrinkable boot arrangement.

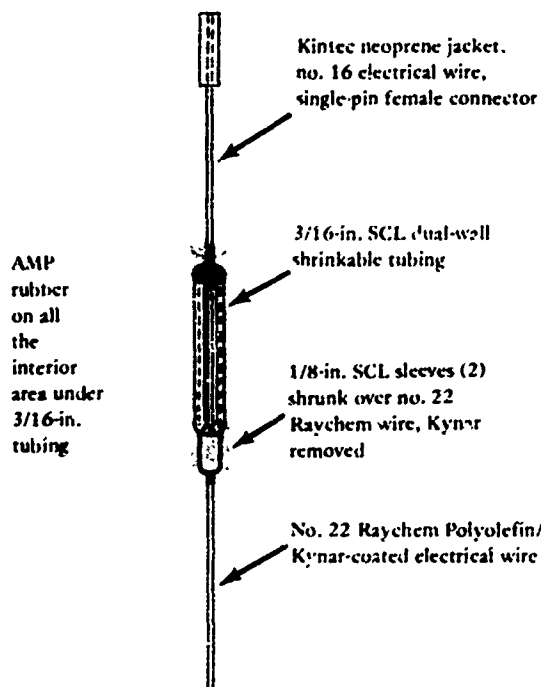


Figure 3-8. Splicing technique using AMP dielectric sealant confined with heat-shrinkable boots.

Before settling on the exact technique to adopt for the SEACON II termination and splicing, a final test sample lot of 50 straight splices was made. These splices were tested in the pressure vessel and then placed in the ocean in shallow water for 3 months. At the end of these tests only one sample had failed. The failure occurred in the ocean, but it is unknown if it was caused by mechanical damage or by poor splicing technique.

The AMP dielectric sealant confined with heat-shrinkable boots (Figure 3-8) was used exclusively for all end terminations and in-line splices of the SEACON II EM cables. Over 100 splices were used in the system. Approximately one-quarter of these were made at sea during the implant operation. No failures of the splices occurred during the 22 month implantment period.

## Findings and Conclusions

1. A simple and reliable technique was developed for terminating and splicing electrical conductors with cross-linked polyethylene insulation.
2. Because of its simplicity and reliability, this technique is also an excellent choice for use on easier-to-bond-to materials, such as polyurethane or neoprene, especially under field conditions.

## Recommendations

Whenever possible one should avoid the use of polyethylene insulation where splices will be in an underwater environment. If this is not possible, the method developed herein is reliable and simple, uses off-the-shelf materials, and requires no special equipment.

## ANCHORS

### Design Criteria

To meet system requirements it was decided to use two separate classes of anchors to moor the SEACON II structure. The classification was based on whether or not a crown line was needed for installation and recovery of the anchor. Two of the anchors were to be used without a crown line and the third one with a crown line.

If feasible, either the deep water explosive embedment anchor or vibrating embedment anchor, both being developed by CEL, would be used without crown lines to anchor two legs of the trimoor. To meet design requirements the anchors had to resist pullout under a long-term (2-year) static load of 3,000 pounds applied at a 10-degree angle with the seafloor and short-term (30-minute duration) vertical loads up to 10,000 pounds that might be applied during construction. It was expected that if the short-term requirement could be met, the long-term one also would be met.

The third anchor to be used with a crown line had to provide a platform for a power system contained

in a 5-foot-square by 4-foot-high box. For handling purposes it could not be larger than 10 feet square by 4 feet high. The anchor had to be stable under a static vertical load of 8,500 pounds and a horizontal load of 1,000 pounds. The maximum allowable tilt the equipment on the anchor could sustain was 15 degrees.

#### Concepts Investigated

The explosive and vibratory embedment anchors were both investigated for mooring two legs of the structure. The vibratory anchor was rejected based on evaluation tests conducted in 6,000 feet of water. The major weakness in the system was that the installation ship had to station-keep very accurately for up to 1 hour while the fluke was being vibrated in. If the ship moved significantly, the anchor support frame would overturn, preventing the anchor from embedding.

In order to evaluate the suitability of the explosive embedment anchors and determine the proper fluke size, embedment anchor tests were performed at the SEACON II site. Short-term pullouts of 30,000 and 27,000 pounds for the 1-1/2 x 3-foot and 2 x 4-foot flukes, respectively, were obtained. Based on analysis of the test data it was determined that the explosive embedment anchor would meet all design criteria for anchor installation without a crown line.

The only concept considered feasible to meet the design criteria for the anchor with a crown line and to also double as a platform for the power system was a clump-type anchor. Uplift resistance is provided by dead weight. Excess tilt or settlement is prevented by having sufficient bearing area to spread the load or by founding part of the foundation deep enough so only competent soils are loaded. Lateral resistance is provided by a keying skirt around the perimeter or by piles. Since piles pose installation problems, it was decided the design criteria could be satisfied by using a spread footing with a perimeter skirt.

#### Anchor Descriptions

The deep water explosive embedment anchor depicted in Figure 3-9 was used to moor two legs of the SEACON II trimoor. The anchor assembly weighs about 1,500 pounds and can be safely handled with

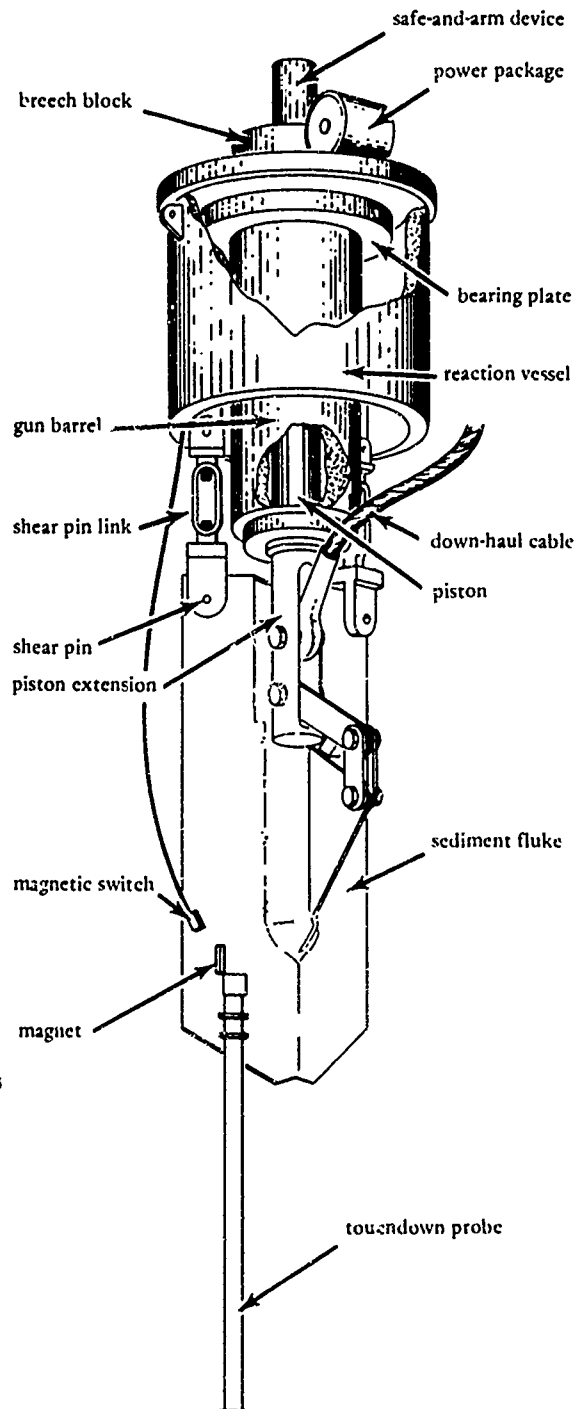


Figure 3-9. Schematic of deep ocean embedment anchor.

the 1/2-inch-diameter wire rope mooring legs. The downhaul cable that is attached to the fluke and penetrates the water-sediment interface (a potentially high corrosion area) is a 3/4-inch-diameter line. The anchor reaction vessel and gun barrel assembly were attached to a hook on the mooring line that was designed to release during the setting of the anchor fluke, thereby allowing the assembly to fall free.

The clump anchor has an air weight of 16,000 pounds and an in-water weight of 12,500 pounds. The anchor is composed of a 7-foot by 8-foot by 2-1/2-inch-thick steel base plate with a 5-foot by 6-foot by 4-foot-high container mounted on top. This container was filled with concrete around the cavities molded into the concrete to contain the radioisotope thermoelectric generator (RTG) and other electronic and power equipment. A metal skirt around the perimeter of the anchor extended 6 inches below the anchor base plate to key the anchor in the sediment.

#### Anchor Performance

The two explosive embedment anchors used in the trimoor plus a third one used to anchor the single-point construction mooring buoy were installed routinely during a single work day. No problems were experienced with them, either during installation or the nearly 2-year life of the structure. During an inspection of SEACON II with the CURV II vehicle, embedment anchor A2 was discovered to be embedded only 8 feet. However, when the structure was recovered, mooring leg L2 parted at a load of 19,000 pounds without breaking the A2 anchor fluke out of the bottom. In contrast, anchor A1 pulled out at a load of 3,500 pounds although a 10,000-pound load had been used to set anchor A1 during implant. As discussed earlier, other evidence indicated a deep trawl had become entangled with leg L1, ripped the cable jacket, and apparently nearly failed the anchor.

The reaction vessel at anchor A1 was found attached to the recovered mooring line. Apparently due to an oversight during the installation process a safety wire had not been removed from the release hook on the mooring line to allow it to operate. The reaction vessel simply acted as a small deadweight anchor in series with the embedded fluke. However, there was no evidence of damage due to the reaction vessel remaining attached.

The explosive embedment anchor on the construction moor underwent the most rigorous testing during the 2-year implant. The mooring had a scope of only 1.4:1. Numerous vessels the size of CIEL's warping tug (120-foot by 135-foot beam) and smaller moored to it. On one occasion in a sea state 5-6 condition, a 70-foot-long deep sea fishing vessel rode on the moor for a day.

During the structure recovery operation the construction mooring anchor was pulled out while load and displacement were monitored. Figure 3-10 shows the Precision Depth Recorder record from a pinger on the mooring line during pullout. The record of direct and reflected pinger pulses, depicted as the two dark lines, indicates the height of the pinger above the bottom. As the anchor fluke exits the seafloor, it is detected by the acoustic signal reflected off it. Correlating these displacement data with the load record yields Figure 3-11, the load-displacement curve for the short-term anchor pullout. This record indicates the embedment depth of the set fluke was approximately 30 feet. After the anchor was moved to mobilize the maximum resistance of the sediment, a peak load of approximately 27,000 pounds was recorded, well in excess of the nominal 20,000-pound design capacity of the anchor.

The embedment depth for the anchors ranged from 8 to 30 feet. Maximum pullout resistance ranged from 3,500 to 27,000 pounds. Discounting the low pullout reading on anchor A1 because of the evidence it had been heavily loaded by an entangled trawl, the peak pullout range was from at least 19,000 pounds for leg L2 that parted during pullout to 27,000 pounds for the construction moor anchor.

The sediment samples from the flukes of the two recovered embedment anchors were very different from one another. As discussed in the site investigation section the evidence shows considerable areal variability exists in the sediment at the SEACON II site. The site variability probably caused the significant differences in embedment depth attained by the flukes.

The 16,500-pound clump anchor performed satisfactorily. There was no evidence of significant lateral movement of the anchor during the implant period based on acoustic transponder navigation fixes obtained periodically. The vertical perimeter keying skirt, which was designed to provide lateral stability,

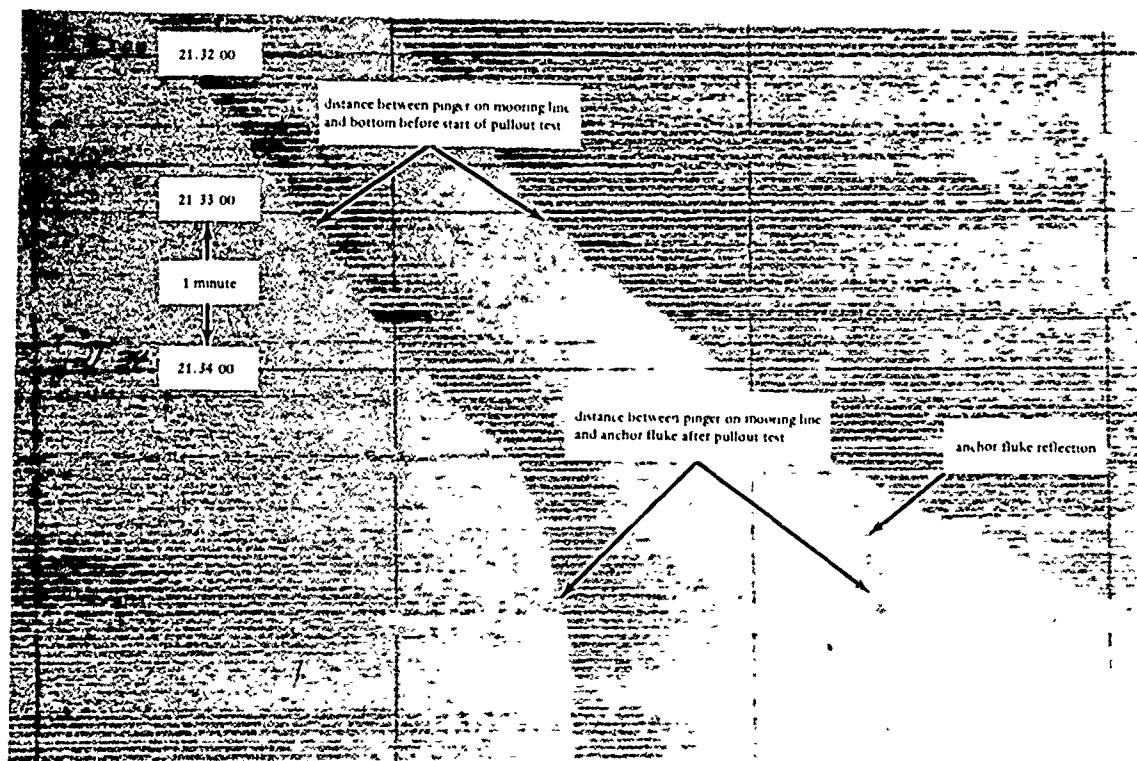


Figure 3-10. Precision depth recorder record of pinger on mooring line during pullout test. Difference between two distances marked on record indicates anchor penetration depth.

appeared to have embedded evenly as evidenced by the mudline on the clump. The mudline also indicates the clump did not settle significantly. In fact, at some locations on the perimeter, the mudline was not quite even with the bottom of the 7-foot by 8-foot base plate, apparently indicating the vertical load was being carried by the perimeter skirt and only part of the base plate area.

#### Findings and Conclusions

1. The explosive embedment anchors were very convenient to install and provided a satisfactory moor for the SEACON II trimoor and single-point construction moor for a 2-year period.
2. Two of the three embedment anchors essentially met or exceeded the nominal 20,000-pound holding capacity goal for the anchors and met design goals for the SEACON II structure. Disturbance of the third anchor, apparently due to entanglement of leg L1

with a trawl, prevented determination of maximum pullout resistance for it.

3. A large variation in anchor embedment depth occurred which was probably due to the wide variation in sediments present at the site. This did not appear to seriously affect anchor holding capacity.

4. An oversight during implant which allowed one anchor reaction vessel to remain on the mooring line appeared to cause no damage to the line.

5. The embedment anchor for the construction moor was able to sustain repeated dynamic loads estimated to be in excess of 10,000 pounds with no adverse effect on the moor.

#### Recommendations

1. Continue development of the explosive embedment anchor so that it can be used in the Fleet in other than very exotic applications.

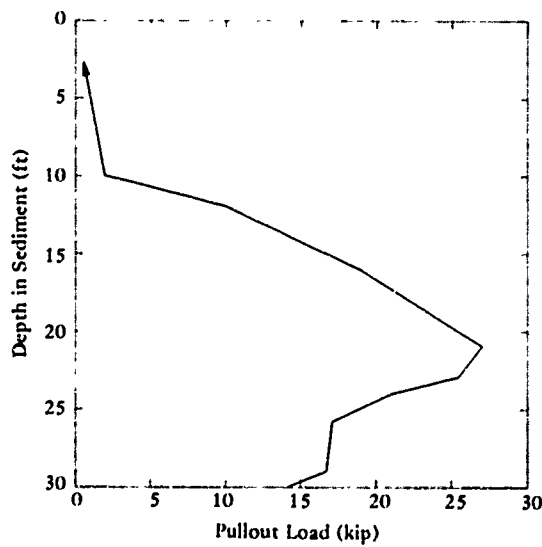


Figure 3-11. Load-displacement record for short-term pullout test on mooring line embedment anchor. Record indicates embedment depth is 30 feet and peak pullout load is 27,000 pounds.

2. Continue obtaining field data on explosive embedment anchor performance to allow more confident application of short-term test data to expected long-term anchor performance.
3. Continue obtaining field data on explosive embedment anchor performance under dynamic loading conditions, varying the loading frequency and the ratio of dynamic load to expected maximum long-term pullout load.

#### BUOYANCY AND INSTRUMENTATION HOUSINGS

The SEACON II trimoor had four major buoyancy elements: one at the upper end of each leg (node buoys), and one at the top of the crown line (crown buoy). Additional buoyancy was provided by the instrumentation housings located in-line and in the node buoys and crown buoy.

#### Design Criteria

The major buoyancy elements were required to be highly reliable against failure due either to overstressing or slow leakage. Failure of any of the four major buoys would have been catastrophic to the SEACON II experiment. The four major buoys were to be spherical, because it is the most efficient shape to resist hydrostatic pressure and the least expensive to design and fabricate. The net buoyancy of the node buoys was to be approximately 1,700 pounds each, and it had to remain constant (within 1%) over the 2-year design life, since accurate knowledge of the buoyancy was essential to a successful validation experiment. It was also desired to minimize the node buoy size so that the drag force on the buoys would be a small percentage of the total drag on the structure. A cavity in the interior of the buoys was required to contain instrumentation housings.

The instrumentation housings also had a requirement for high reliability against leaking or being overstressed. However, a single failure would not be catastrophic to the SEACON II experiment because of redundancy and electrical isolation of the electronics canisters. Minimizing size and weight, providing a convenient shape for packaging the electronics, and designing for ease of access to the interior of the housings were all considered important design criteria.

#### Concepts Investigated

Syntactic foam and steel were the two prime material candidates for constructing the node buoys. Both materials would result in buoys approximately 5 feet in diameter that could easily be designed to accommodate the instrumentation housings. The foam buoy posed more problems in terminating the cables than the steel buoy did. However, syntactic foam appeared less likely than steel to sustain a catastrophic failure. A syntactic foam material that could be fabricated into buoys at a cost comparable to steel buoys was found. Although the manufacturer claimed less than 1% water absorption, users of the foam had experienced considerably more than the 1% [3-3]. Because unknown buoyancy change due to





Figure 3-12. Node buoys being delivered to CEL pressure vessel for pressure tests and buoyancy measurements.

water absorption was unacceptable, it was decided to fabricate the node buoys from steel, using fabrication and testing methods that would give high assurance of integrity.

Based on the same reasoning as for the node buoys, it was also decided to fabricate the crown buoy of steel.

The choices of shapes, materials, and configurations for instrument housings narrowed quickly. To be in concert with the mechanical guidelines adopted for design, it was decided to fabricate the housings of steel. A cylindrical shape with one removable end was also selected as the most convenient form for packaging and accessibility to the electronics.

#### **Buoyancy and Instrumentation Housing Descriptions**

The node buoys (Figure 3-12) were 5-1/2-foot-diameter steel spheres, weighed about 3,000 pounds

in air, and had a net buoyancy in seawater of about 1,700 pounds. The crown buoy was an 8-foot-diameter steel sphere, weighed approximately 5,000 pounds in air, and had a net buoyancy of about 12,000 pounds. All the buoys were designed and fabricated according to the ASME Boiler and Pressure Vessel Code, Section VIII, Division II. This required full penetration welds inside and out, x-ray inspection of all welds, and hydro-testing of the completed buoys.

Each node buoy contained a closed-ended cavity in which the node instrumentation canister was located. The crown buoy had a pipe through the center for stowing the crown buoy instrumentation canister; this pipe also acted as a strength member through the buoy. The cable termination canisters (Figure 3-13) were bolted to the bottom of each node buoy to make the buoys more stable during implant. Two horizontal arms and one leg were attached to each termination canister in a bail joint connection:

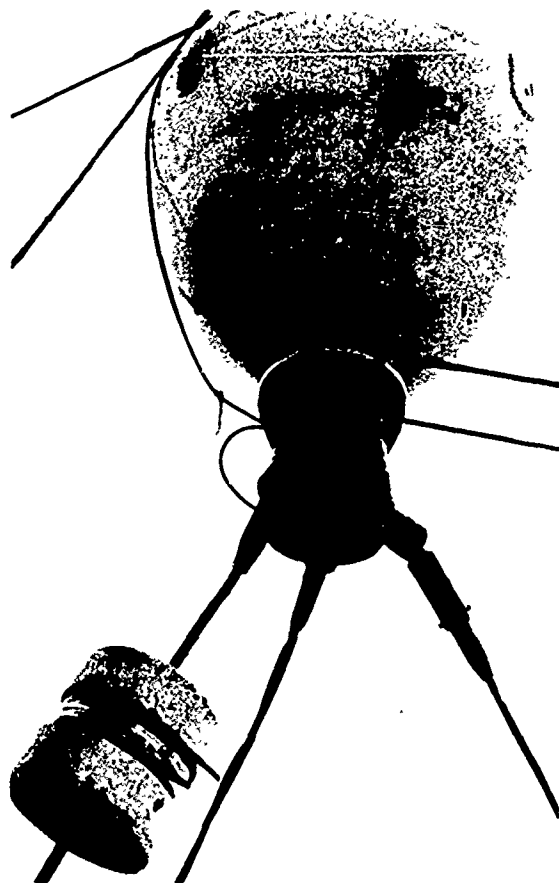


Figure 3-13. Cable termination canister mounted on node buoy. Hydrophone visible at base of canister. Three DYNA-GRIP ball joints terminate at canister.

the electrical cables were fed through the middle of the ball joint to the instrumentation housing.

The cylindrical instrument housings, which were located at the node and crown buoys, were designed with dual O-rings - one barrel and one face seal - on their covers to increase reliability against flooding. Single barrel seals were used on the housings that were less critical. All of the housings were pressure-tested prior to installing the electronics to further insure against failure.

The design and performance of the corrosion protection system for the buoys and housings are presented in Appendix A.

## Results and Discussion

After the node buoys were delivered from the fabricator, the access hatches were removed to inspect the O-rings and O-ring surfaces. It was found that these areas had not been protected when the buoys were sandblasted prior to painting. The result was serious pitting of the O-ring grooves. To correct the problem it was necessary to weld the hatches shut. Despite this initial problem all of the buoys performed satisfactorily. No evidence of overstressing on any part of the buoyancy assemblies was noted, and no water leakage occurred. As noted in Appendix A no significant corrosion was found on any part of the buoyancy elements. Terminating the cables at the bottom of the node buoys worked well. The buoys were stable in the water, and no tendency to twist or entangle the cables was noted.

All but one of the 11 instrument housings performed satisfactorily. As discussed in the implant description one of the midline hydrophone canisters leaked as soon as it was installed and quickly flooded. Later inspection determined the leak was probably due to an improperly tightened bulkhead electrical penetrator. There appeared to be no fault in the design of the housing. The housing located in the crown buoy was opened and closed and installed more than a hundred times without sustaining any leakage.

## Findings and Conclusions

1. To meet the design criteria, steel was selected as the material for the four major buoyancy elements in the SEACON II structure. A serious drawback to using the other major candidate, syntactic foam, was its water absorption.
2. By using the ASME Boiler and Pressure Vessel Code, Section VIII, Division II, buoys were designed and fabricated that maintained structural integrity and did not leak during an installation period of nearly 2 years.
3. The design of the instrument housings, which used both double and single O-ring seals, worked satisfactorily. The crown buoy canister with a double O-ring seal was opened and closed in excess of 100 times without leakage occurring.

### Recommendation

Syntactic foams that are presently available on the market should be evaluated to determine how well they meet manufacturers' claims and what development efforts, if any, should be supported to reduce cost and improve quality control.

## SECTION 3 - STRUCTURE RESPONSE MEASUREMENT SUBSYSTEM

The instrumentation for the SEACON II structure was designed to measure the response of the structure to the ocean environment expected at the site. The measurement accuracies of the instruments were specified based on the results of the parametric analysis described earlier. Instruments were located at all major nodal points on the structure and at a limited number of intermediate locations to completely define the response of the structure. Redundant measurements were provided to insure sufficient data would still be obtained in the event some equipment failures occurred.

The instrumentation was designed to make three types of measurements automatically as often as 4 times per hour: acoustic position, pressure (depth), and tension. The three-dimensional acoustic position measuring system was the primary source of response data for validating the computer program. The pressure or depth sensors were designed to provide redundant data as a backup to this system. Tension measurements provided an independent backup method to determine structure response in case the acoustic positioning system did not operate or did not meet accuracy requirements.

The response measurement subsystem included not only the instruments for making the desired measurements but all of the supporting equipment, including control and recording hardware and power equipment.

### DESIGN CRITERIA

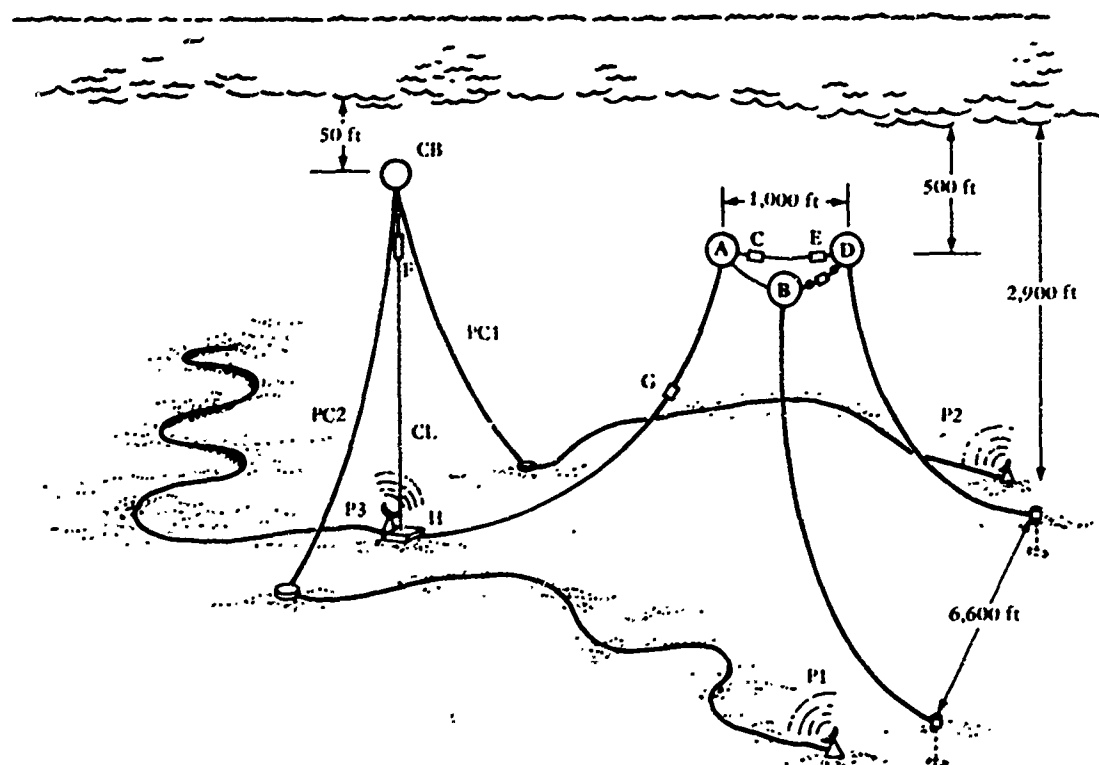
The design criteria for the structure response measurement subsystem are:

- The three-dimensional location of the positioning stations on the structure should be measured to a relative accuracy over a period of days of  $\pm 1$  foot.
- Pressure at instrument stations should be measured to a relative accuracy of  $\pm 0.25$  psi (approximately  $\pm 0.6$  foot).
- Tension should be measured to a relative accuracy of  $\pm 5$  pounds.
- All data to be automatically recorded once each hour with the capability to decrease cycle time to 2 or 4 times per hour. Each complete scan of data should require less than 5 minutes.
- A capability should be provided to obtain position data from selected stations at 30-second intervals.
- Data recorder and as much other electronic equipment as practicable should be housed in crown buoy canister, which is SCUBA-diver recoverable for servicing.
- The recording, control, and power system located in the crown buoy should operate a minimum of 1 month unattended at a sampling rate of 1 cycle per hour.
- The power equipment, except that portion located in the crown buoy, should operate unattended for 2 years with automatic cycling once each hour.
- The overall system power must have redundancy and also be capable of operating on surface-supplied power. Individual instruments need not meet requirements set for the overall system.

### MEASUREMENT EQUIPMENT

#### Acoustic Positioning

The acoustic positioning network was designed to measure the slant range distances from three acoustic projectors (P1, P2, and P3) to each of seven hydrophones located at data acquisition canisters A through G (Figure 3-14). To achieve a relative



accuracy of better than  $\pm 1$  foot from one measurement cycle to the next over a long period of time, it was necessary to take three types of measurements—gross distance, refined distance, and sound velocity.

**Gross Distance Measurement.** The gross distance measurements between the projectors and hydrophones were accomplished by using an acoustic pulse technique in which the transmission of a pulse from each projector to each hydrophone is timed. Figure 3-15 shows the sequence of events that take place in making this measurement.

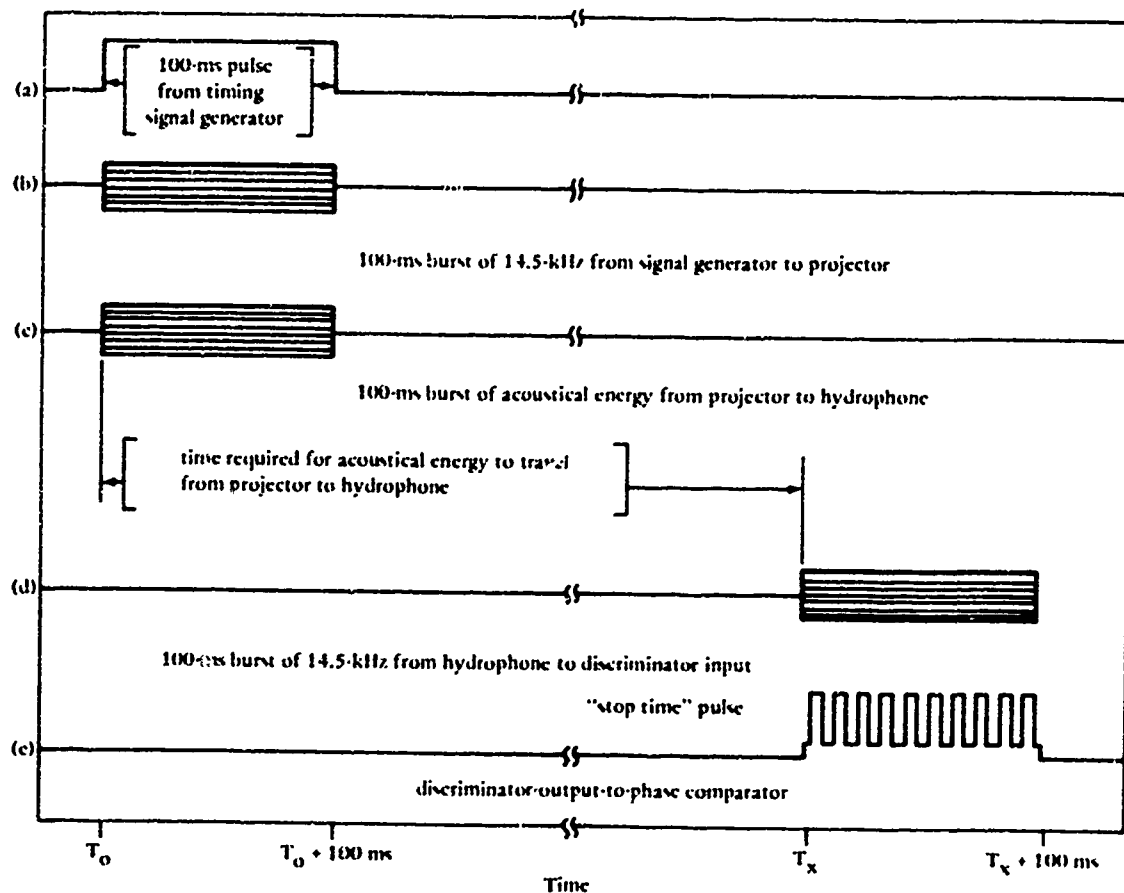


Figure 3-15. Gross distance measurement signals.

**Refined Distance Measurement.** A phase comparison technique was utilized to reduce the error inherent in the gross distance measurement. A 100-Hertz square wave from the timing signal generator modulates the 14.5-kHz signal to the projector and is also applied to one input of a phase comparator. The modulated pulse is transmitted by a projector, received at a hydrophone, transmitted electrically to the crown buoy canister, and applied to a discriminator as described under the gross position measurement section above. The discriminator strips the 14.5-kHz carrier signal and applies the 100-Hertz signal to a second input of the phase comparator, as shown in Figure 3-15e. As the negative going edge of the 100-Hertz signal from the timing signal generator goes through zero, the phase

comparator output goes high (see Figure 3-16). As the negative going edge of the discriminator output goes through zero, the phase comparator output goes low. The resulting phase comparator output is a series of ten pulses with the peak duration of each pulse equal to the phase difference between the two inputs to the phase comparator.

To accurately determine the average phase difference, the number of cycles of a 100-kHz signal is counted during the periods when the phase comparator is at its peak. This count is taken over a 60-ms period, as shown in Figure 3-16. The total number of cycles counted is equivalent to a period of time measured in increments of  $10^{-5}$  second. Each increment is, thus, equal to a travel distance in water of approximately 0.05 foot, which becomes the

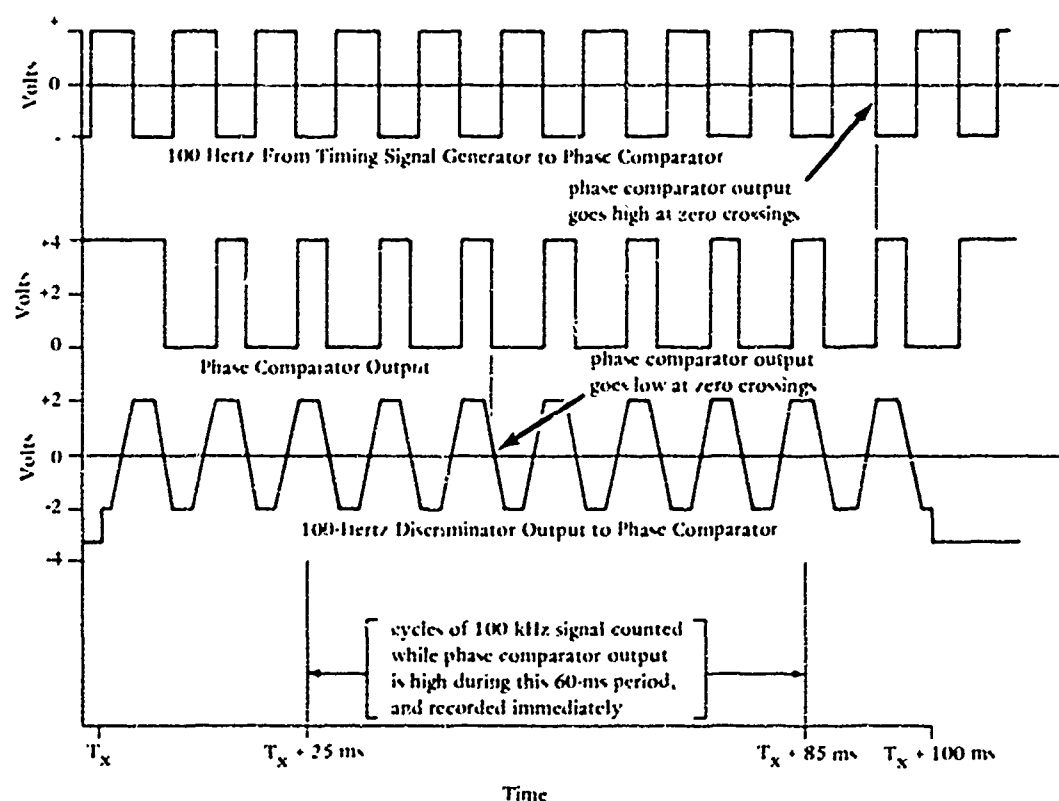


Figure 3-16. Phase measurement signals used to determine phase difference between transmitted acoustic signal and timing signal.

theoretical sensitivity limit of the phase measurement system. The resulting count ranges between 0 and 6,000 depending on whether the two inputs to the phase comparator are exactly in phase or as much as 360 degrees out of phase. To obtain the total "refined" slant range distance between a projector and hydrophone, the number of full 100 Hertz cycles (10-ms periods) determined during the gross distance measurement is added to the time shift of the 100 Hertz signal determined by the phase comparison technique. This total time represents a very precise measurement of the time required for the acoustic signal to travel between an acoustic projector and hydrophone.

**Sound Velocity Measurement** In order to convert the time for the acoustic pulse to travel between a projector and hydrophone to the distance

between them, the average sound velocity over the transmission path must be known. For this reason a means to accurately determine the average sound velocity between the bottom, where the acoustic projectors were located, and 500 feet below the water surface, where all but one of the hydrophones were stationed, was devised. The distance between projector P3 (see Figure 3-14) on the clump anchor and hydrophone F on the crown line was accurately measured before installation. The taut crown line moor was designed to have an excursion of less than  $\pm 1.0$  foot vertically under the highest current profile expected at the site. During each data-taking cycle the transmission time for the acoustic signal between projector P3 and hydrophone F was measured. With known time and distance the average sound velocity between 500 feet and the bottom could be calculated.

### Pressure Measurement

Pressure transducers were located at each acoustic node A through G (see Figure 3-14) to provide redundant data for calculating structure position. Each transducer was subjected to pressure at the water depth at which the hydrophones for determining acoustic position were located.

To acquire pressure data, regulated DC power was applied to a bridge-type pressure transducer. The transducer output was amplified and applied to a voltage-to-frequency converter. The converter output signal was amplified and transmitted to the crown buoy canister through the EM cables.

The cycles of the incoming signal were counted for 0.5 second and recorded. Two seconds after power was applied to the pressure transducer, a calibrate resistor was shunted across one arm of the transducer bridge. The resulting change in bridge output caused a change in frequency output of the converter. The cycles of this signal were also counted for a period of 0.5 second and recorded. The change in cycle count due to the shunt calibrate resistor provided a calibration constant for use during data reduction.

The six pressure transducers at A through F are rated at 350 psi, while the one at G is rated at 1,000 psi. The transducer manufacturer claims a repeatability of  $\pm 0.03\%$  of rated output, which corresponds to approximately  $\pm 0.2$  foot and  $\pm 0.6$  foot, respectively. To take advantage of the high degree of repeatability and to avoid error due to any non-linearity, the 350-psi transducers were calibrated in CEL's pressure facility over the range of 170 to 270 psi, which corresponds to the expected range. Based on the calibration, the relationship of the change in output frequency of the converter due to change in pressure on the transducer, to the change in frequency due to the shunt resistor was established. The relationship remains constant regardless of changes in power applied to the transducer or changes in amplifier gain.

### Tension Measurement

Tension transducers were located at five positions on the structure at the ends of all three cables terminating at node A (Figure 3-14), at the node D

end of the delta cable between A and D, and at the bottom of the leg terminating at the clump anchor (H). The tension transducers provided an independent method for validating the analytical computer model should the positioning system fail to operate as designed.

Because no off-the-shelf transducers suitable for this application were found, CEL designed and fabricated the transducers in-house. A description of the transducer developed is provided in Appendix B. The tension element is a hollow steel tube with strain gages in a bridge configuration. To provide the sensitivity to achieve a  $\pm 5$ -pound relative accuracy, the steel tubes were made very thin and were designed to fail at a load of 2,500 pounds. In order for the tension cells to survive, maximum tensions (static plus dynamic) had to be kept to 2,000 pounds during implant. Since the breaking strength of the cable (approximately 25,000 pounds) had to be the weak link in the system, the tension cells were designed with a fail-safe collar to take up the load if the tension measuring tube failed.

Three-hundred-and-fifty-ohm gages were used to allow sufficient voltage to be applied to the bridge to obtain the desired output signal while conserving on power. The procedure for measuring and recording the tension sensed by the tension transducers and for calibrating the transducers was the same as that used for the pressure measurement.

## TIMING, CONTROL, AND RECORDING

### Timing Equipment

The crown buoy electronics canister was designed so that complete data cycles could be taken automatically once each hour, half-hour, or quarter-hour. A full cycle of measurements, including recording, required 3 minutes 54 seconds.

The time periods and sequence of measurements were controlled by signals from the timing signal generator located in the crown buoy electronics canister (see Figure 3-17 for block diagram). As discussed earlier, the timing signal generator also furnished a 100-Hertz square wave to frequency-modulate the 14.5-kHz VCO, and a 10-kHz and 100-kHz signal for measuring distances between the projectors and the hydrophones.

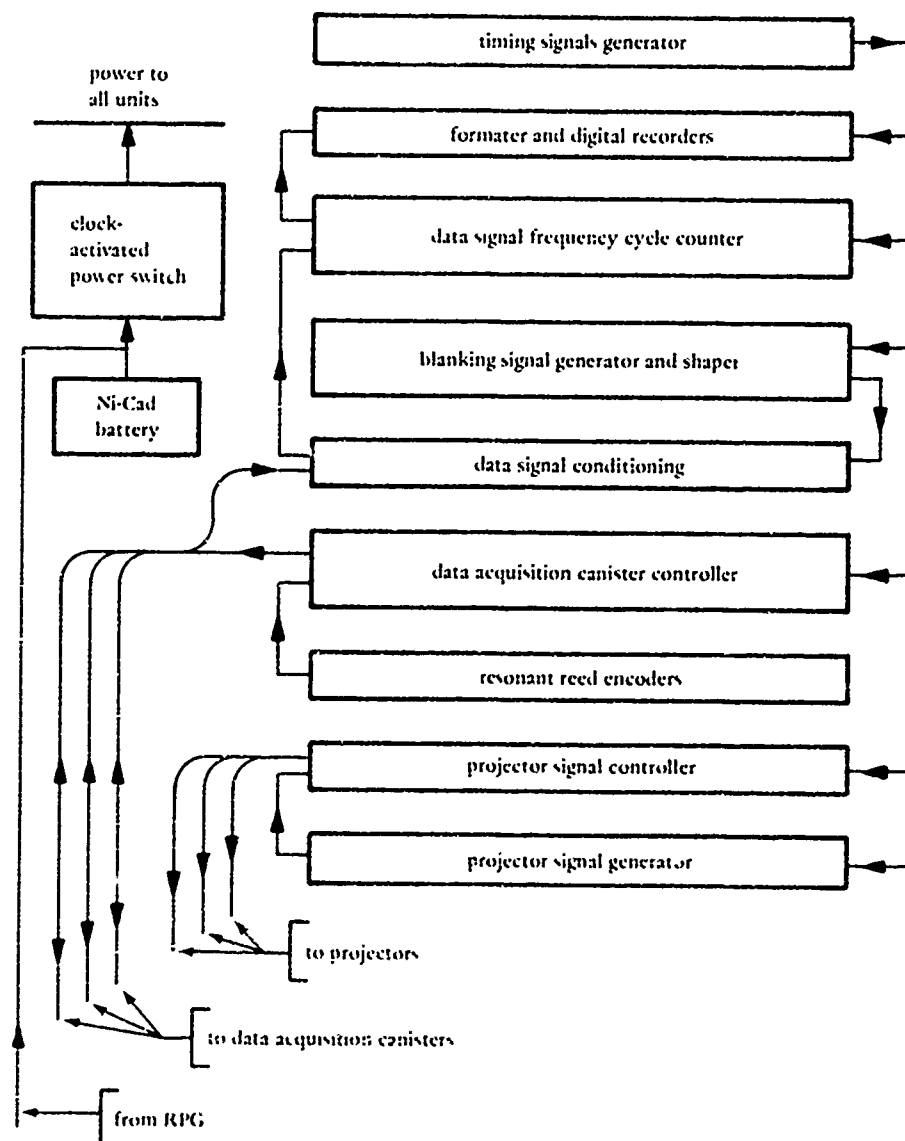


Figure 3-17. Block diagram of crown buoy electronics.

#### Turn-On of Data Acquisition Equipment

Power was delayed 15 seconds to the timing signal generator after the crown buoy canister equipment was energized to allow the resonant reed encoders to come up to full power. Each data acquisition canister was turned on by a specific frequency generated by an encoder. Immediately after power was applied to the timing signal generator, a

positive voltage output of 1.5 seconds duration was furnished. The signal was processed and applied to gates, which caused an encoder output to be applied to all data acquisition canisters through the conductors of the FM cables. The data acquisition canister turned on approximately 40 ms after the encoder signal was applied to the FM cable. Figure 3-18 is the block diagram of the data acquisition canisters, and Figure 3-19 shows a typical data



sampling sequence. Two seconds after a data acquisition canister turned on, the data selector energized the hydrophone for 6 seconds to receive the incoming projector signals. Following this, pressure and tension data were collected at 2-second intervals.

#### **Electrical Zero**

After all distance, pressure and pressure calibration, and tension and tension calibration measurements at one data acquisition canister were completed, the input to the transducer amplifier was shorted. The system was designed such that with the input shorted, the amplifier had an output signal from the voltage to frequency converter. This signal was designated electrical zero. The cycles were counted for 0.5 second and recorded. Any change in the electrical zero reading had to be applied as a zero shift to the pressure and tension calibration data used in data reduction.

#### **Turn-Off of Data Acquisition Canister**

After the electrical zero measurement was completed, the data acquisition canister would turn itself off. In addition, a turn-off signal was sent to the data acquisition canister from the crown canister during the last 2 seconds of the time allotted for taking data from that canister. The turn-on signal for the next data acquisition canister to be interrogated was also of a frequency that would turn off the preceding canister. This redundancy insured a data acquisition canister could not be left on to drain the power sources.

#### **Turn-Off (End of Cycle) of Crown Buoy Canister**

The last signal generated by the timing signal generator was conditioned and applied to a relay. The contacts of the relay were maintained closed by a capacitor discharge circuit for the period of time required for the crown canister to reset to the quiescent condition. If the signal from the timing signal generator did not reset the crown canister, a clock-operated switch provided a contact closure to generate a reset signal each 15 minutes.

#### **Verification of System Operation**

The pulse from the timing signal generator that reset the crown canister was also used to advance a stepping switch. The switch made contact, thereby applying voltages from a divider circuit to the input of a voltage-to-frequency converter. During the data recording period, the cycles of the converter output signal were counted for 0.5 second and recorded. The stepping switch was reset every 8 hours. The recorded count was used to verify the system operation during each 8-hour period and to relate time of day to each data cycle.

#### **Data Acquisition Canister Identification (Location)**

In addition to recording data from the data acquisition canisters, the cycles of the encoder signal used to turn on the data acquisition canisters were counted for 0.5 second and recorded. During data reduction the count verified which measurement station the subsequent recorded data came from.

#### **Redundant Data Transmission Lines**

Each time the data acquisition canister turned off, a pulse was generated that connected the line driver to a different conductor in the EM cables. The three conductors in the cables were scanned in sequence to assure an open or shorted EM cable conductor would not result in the loss of all data. The encoder signal that turned on the canister was applied to all three conductors to make sure the canister could turn on even if two of the three EM cable conductors were shorted.

#### **POWER**

The heart of the power system was a 10-watt radioisotope thermoelectric generator (RTG). The unit, which weighs 645 pounds, is a SNAP-21 supplied by the Naval Nuclear Power Unit. The generator is fueled by strontium 90 in titanate form and is contained in a 16-inch-diameter, 25-inch-high pressure hull with a pressure rating of 10,000 psi. Power is provided at 48 volts DC regulated.

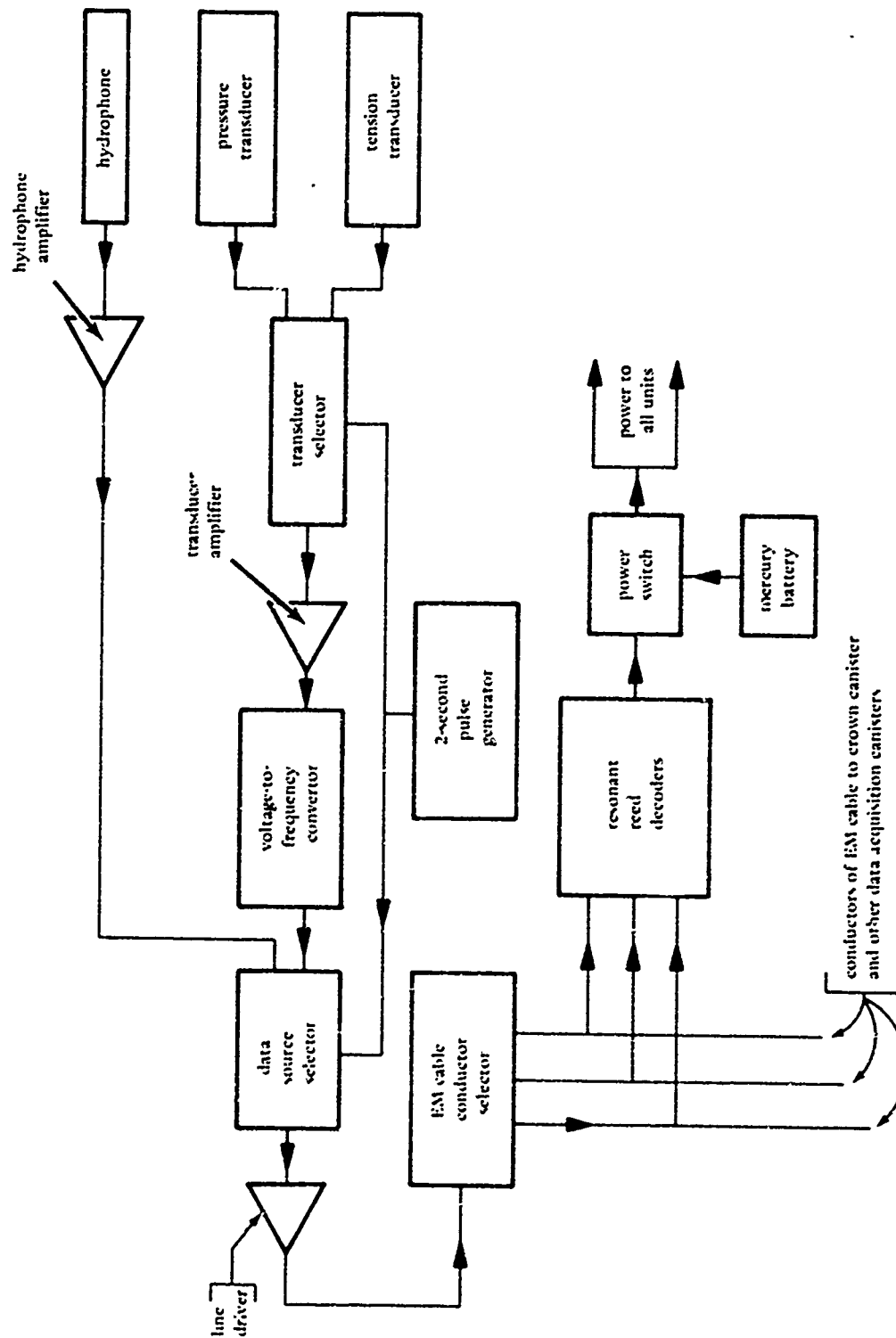


Figure 3-18. Block diagram of data acquisition canister.

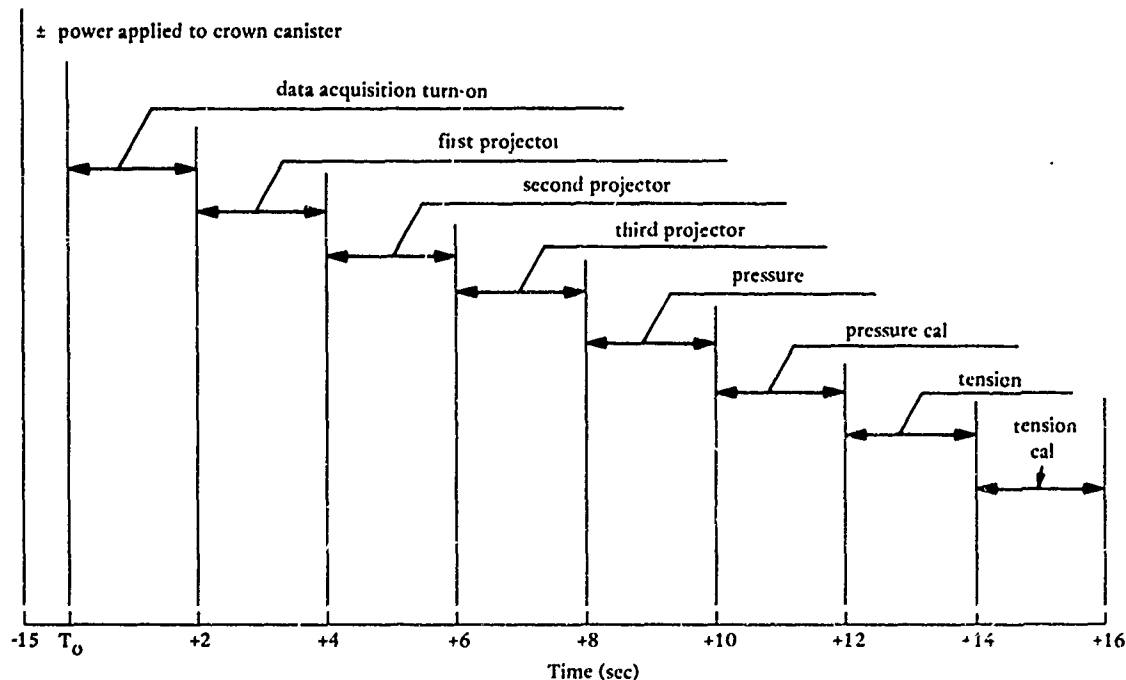


Figure 3-19. Typical measurement sequence at a data acquisition canister sensor station.

As shown in Figure 3-20, the RTG, which was located in the clump anchor, charged capacitors at each of the three acoustic projectors and the Ni-Cad battery bank located in the crown buoy canister.

Since the RTG supplied the overall system power and its failure would be catastrophic to the SEACON II experiment, a backup power source was also provided. A 520 ampere-hour lead-acid battery with an output at 48 volts DC was located alongside the RTG in the clump anchor. Should the RTG drop below 28 volts, the lead-acid battery would be switched in automatically. If the RTG voltage returned to normal, it would be switched back on line automatically.

A 4 ampere-hour Ni-Cad battery pack located in the crown buoy canister was trickle-charged at about 150 ma to supply power for operating the electronic equipment in the crown buoy canister.

A third means for supplying power to the system should the RTG/lead-acid battery combination fail

was via an umbilical to a surface vessel. Should unattended power be desired, additional batteries could be placed in a housing and attached to the crown buoy by SCUBA divers.

Figure 3-20 shows the distributed power used at each of the eight data acquisition canister stations serving the acoustic nodes and pressure and tension sensors. The power at these stations was supplied by primary mercury cells, which, of course, are not rechargeable. Since each data acquisition station was completely independent, the failure of one would not result in any other failures. Therefore, this distributed power system met the design criteria.

## RESULTS AND DISCUSSION

### Performance of Acoustic Positioning System

**Bias Errors in Cross Distance Measurements.** The time measured by counting cycles of a 10-kHz signal

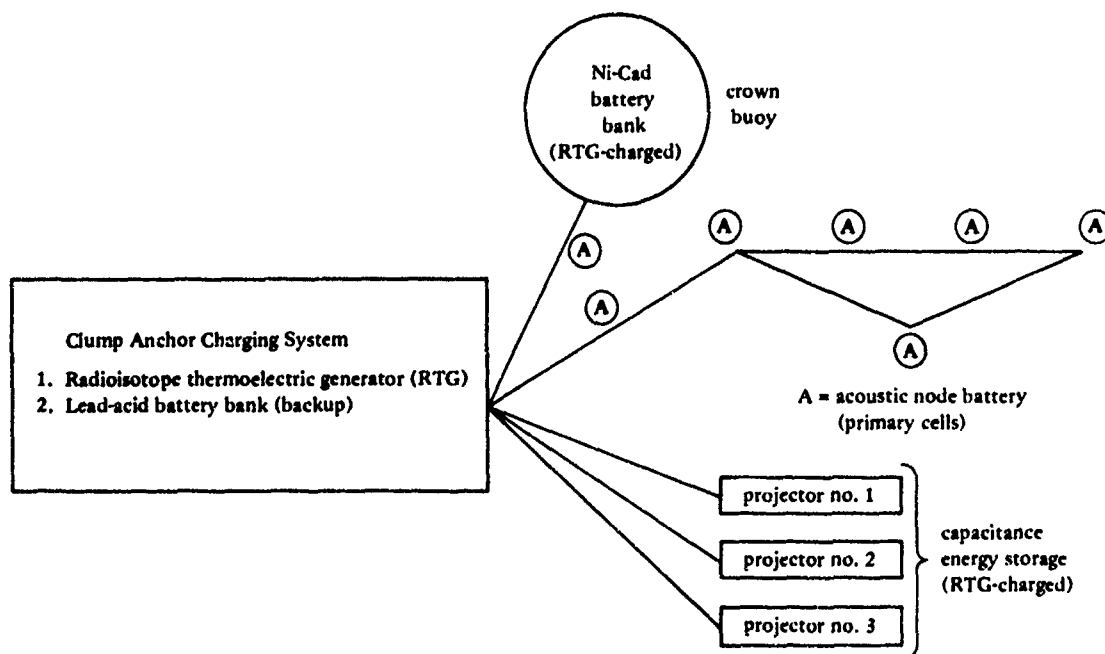


Figure 3-20. Power system for SEACON II.

during the period between start and stop pulses was in error by the time required for the projector, the hydrophone, and discriminator to respond to applied signals. Bench tests showed that the stop count pulse signal was generated up to 0.8 ms after the leading edge of the 14.5-kHz signal was applied to the discriminator. Compared to this delay, the time required for the signal to travel over the transmission wires and the error caused by phase shift of the 14.5 kHz was insignificant. The total of all errors always causes the time measured between start and stop pulses to be longer than the true time required for the acoustic signal to travel from projector to hydrophone. The field data show the error to be a bias of approximately 2.0 ms, which represents a bias in slant distance measurement of about +10 feet.

**Bias Errors in Phase Measurements.** The use of zero crossing of the negative going edge of the 100-Hertz output of the discriminator introduced an error in the phase measurement. The error was caused by the inability of the VCO, the projector, the hydrophone, and the discriminator to respond to a change in input signal in zero time. The VCO, the projector,

and hydrophone responded in a short time compared to the discriminator. Since they all started to respond at the same instant, cancelling the error caused by slow response of the discriminator canceled the entire error.

A bench test was performed to measure the magnitude of the error. The output of the VCO was hardwired to the discriminator input. When the discriminator output was applied to the phase comparator along with the timing signal, a series of measurements of delay time between the signals was obtained. After more than a thousand measurements were completed, the count of cycles of the 100-kHz signal was found to be  $1,200 \pm 12$  Hertz. The 1,200 Hertz was a phase shift or time delay due primarily to slow discriminator response time. This bias error was accounted for during data reduction.

**Random Errors in Acoustic Position Measurements.** To assess the amount of random error in the acoustic distance measurements, data from acoustic node 1 on the crown line were analyzed. This location was chosen because it was designed to remain a constant known distance (within  $\pm 1$  foot) from projector P3 at the clump anchor.

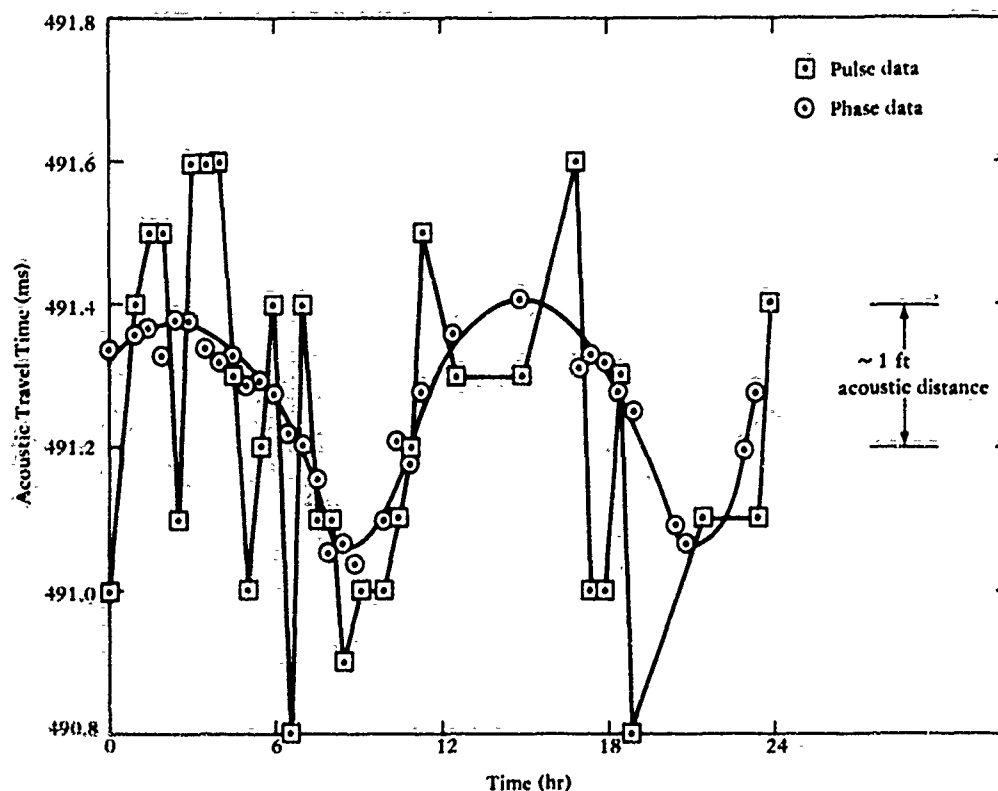


Figure 3-21. Comparison of pulse and phase measurements taken between projector P3 and hydrophone F over a 24-hour period.

Figure 3-21 is a plot of the pulse time measurement between P3 and F during a typical 24-hour period. On the same plot is the pulse time measurement refined with the phase data. A smooth curve through the phase measurements is sinusoidal with a period corresponding to tidal cycles. One possible explanation for this periodic change in travel time is that the average sound velocity between 500 feet and the bottom is changing about 1 fps in 6 hours. This probably is not the cause since other measurements between P3 and F made a month earlier exhibited the same sinusoidal variation but shifted 0.4 ms higher, which indicates the change in average sound velocity in 1 month was only 2 fps. Also, calculation of sound velocity made from physical data collected at the site on 8 June 1972 and again on 26 September 1975 showed the average sound velocity changed only 2 fps in 3 years. Thus, it appears that the average sound velocity at the deeper levels of this basinal site is a very stable property.

Instead of the sound velocity changing, it is believed the sinusoidal variation in travel time between P3 and F is due to the currents, dominated by tidal currents, causing a small catenary in the taut crown line. As the currents increase, the catenary increases, and the distance between P3 and F decreases as much as 2 feet (0.4-ms travel time).

Because it appears the change in sound velocity at this site is a relatively long period phenomenon, a constant value of sound velocity was used to reduce the acoustic position data. Sound velocity was calculated using the measured distance between P3 and F and the peak acoustic travel time when it is believed the smallest catenary existed in the crown line. This approach may introduce a small bias of 2 to 4 feet into the absolute position measurement due to the bias error in sound velocity. However, it is believed this disadvantage is offset by the significant reduction in the magnitude of random error in position measurements.

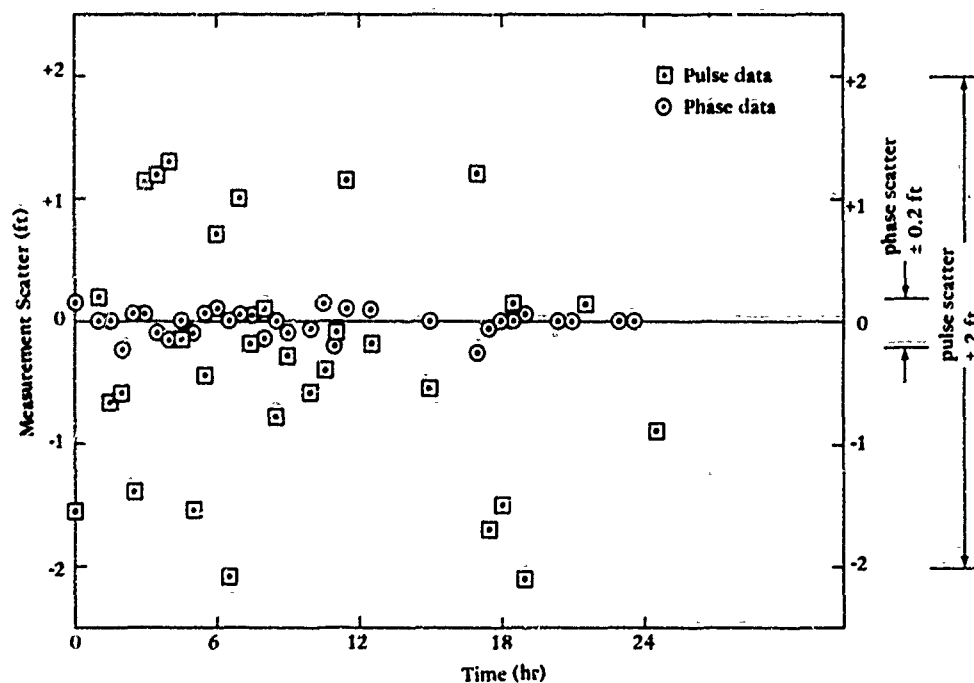


Figure 3-22. Comparison of pulse and phase acoustic distance measurement scatter about datum made by smooth curve through phase data.

To examine the relative accuracy attained with the acoustic position measuring system for both pulse and phase measurements, the data presented in Figure 3-21 were converted from time to distance measurements using sound velocity. The variation of the pulse and phase data about the smooth, sinusoidal curve drawn through the phase data is presented in Figure 3-22. This is a measure of scatter for the pulse and phase data. As can be seen from the plot, the scatter in the pulse data is about  $\pm 2$  feet, while the scatter in the phase data is less than 0.2 foot. This 0.2 foot is only four times the theoretical limit of sensitivity (0.05 foot) of the phase measurement system based on the frequency level and data sampling time used in making the measurement.

When the effect of this 0.2 foot of scatter in the distance measurement between one projector and a hydrophone is combined with the measurements from the other two projectors to a given hydrophone to compute the three-dimensional relative position of the hydrophone, the resulting position is accurate to about  $\pm 0.35$  foot. It is believed this level of accuracy,

better by a factor of three than the design goal, is borne out by the orderly behavior of the measured position data presented in Chapter 6.

**Operational Experience With Acoustic Positioning System.** Although the acoustic positioning system accuracies exceeded the design goal considerable difficulties were experienced in reaching this level. The major problem was caused by reflected acoustic signals from the bottom and surface that triggered the stop time circuitry prematurely at the receiving hydrophones.

This was recognized as a potential problem and was addressed early in the design process. The timing of the system was based on the assumption that the reflected signals would be sufficiently damped after three reflective periods to avoid interference. This assumption turned out to be erroneous; the reflected signals were not attenuated as rapidly as expected. The result was premature stop times at the hydrophones caused by the receipt of strong reflected pulses from a previous projector signal. The problem

was especially difficult and time-consuming to solve, because the times and amplitudes of the incoming reflections varied with sea conditions and because each step in solving the problem had to be checked on site from a small boat.

The small boat was moored to the crown buoy, and communication was established with the structure electronics through an electrical umbilical cable brought to the surface by divers. To further compound the problem, during one of the early checkout cruises the mechanical mooring parted, and the electrical umbilical was ripped out of a junction box on the crown buoy 60 feet underwater. This initiated a series of attempts to make underwater cable repairs which coincided with the effort to solve the signal timing problem.

Numerous other electronic problems added to the difficulty in obtaining good quality data. These included periodic erratic behavior of the digital control and recording equipment in the crown buoy canister, interference from noise generated by electronic equipment in the crown buoy canister, damage to equipment in the canister due to handling aboard ship at sea, and the corrosion effects of the sea environment during trouble-shooting at sea. Often it was difficult to determine if failure to get good data was due to shorts in the underwater electrical splices, problems with the crown buoy electronics unit, or interference from the reflected signals.

The acoustic reflection problem was eventually solved by adding circuits to gate out all incoming acoustic signals until approximately the time when the "good" signal should arrive. The gates were opened at least 40 ms (equivalent to approximately 200 feet travel distance in seawater) before the incoming signal was expected and were left open to insure the "good" signals would not be blocked out.

After implant was completed, it took approximately 7 months before the pulse measurement portion of the system worked with reasonable reliability. An additional 3 months were required to get the phase measurement equipment operational.

Numerous data-taking attempts using the automatic mode with the crown buoy canister housed in the crown buoy were made during the 6-month period after the pulse measurement equipment was operational. During this period approximately sixteen 24-hour days of data recorded at 1/2-hour intervals

were obtained. None of these data had signals from more than two of the three projectors, since P1 had quit operating soon after the structure was implanted. Data from nodes B, E, F, and G were obtained fairly reliably. No acoustic data were obtained from node C, because the hydrophone failed to respond soon after implant. Acoustic data from node D were not available on about the first half of the data collected, and node A acoustic data were missing on much of the second half. Pressure data were reliably recorded from all nodes, and they provided the backup positioning data needed due to projector P1 not operating.

When the data were reduced, the pulse data were found to be quite reliable; however, much of the phase data were erratic, which indicates noise was getting into the system. Using only pulse data to determine excursions of the nodes through tidal cycles resulted in relative position accuracies of about  $\pm 3$  feet. With curve smoothing this could be improved somewhat, but it still would not meet the design goal of  $\pm 1$  foot needed to validate the computer program to the level desired.

With a significant amount of data in hand by October 1975, it was decided to make one last all-out effort to collect the best data possible from the system. Up to this point only partial repairs had been made on the electrical cables which joined at the crown buoy. No attempt had been made to repair projector P1 for fear that more damage might be done to other equipment that was working.

In November 1975, 13 months after the SEACON II structure had been implanted, the rewiring of the projector cables, crown line cable, and umbilical cable at the crown buoy began. Four 1-day cruises were required to perform this critical operation. It was completed on 9 December 1975 with 13 underwater electrical splices being made successfully by C.H. divers. On 11 December 1975 a new current meter string was installed at the site, and data taking began with the crown buoy canister aboard the 70-foot fishing vessel *La Lala*, which was moored to the crown buoy. Between 11 and 19 December, with one interruption for a storm, approximately four 24-hour days of data on a 15-minute cycling rate were recorded. Good pulse and phase data were obtained for all nodes except A and C, with all three projectors operating. The analysis of these data to validate the

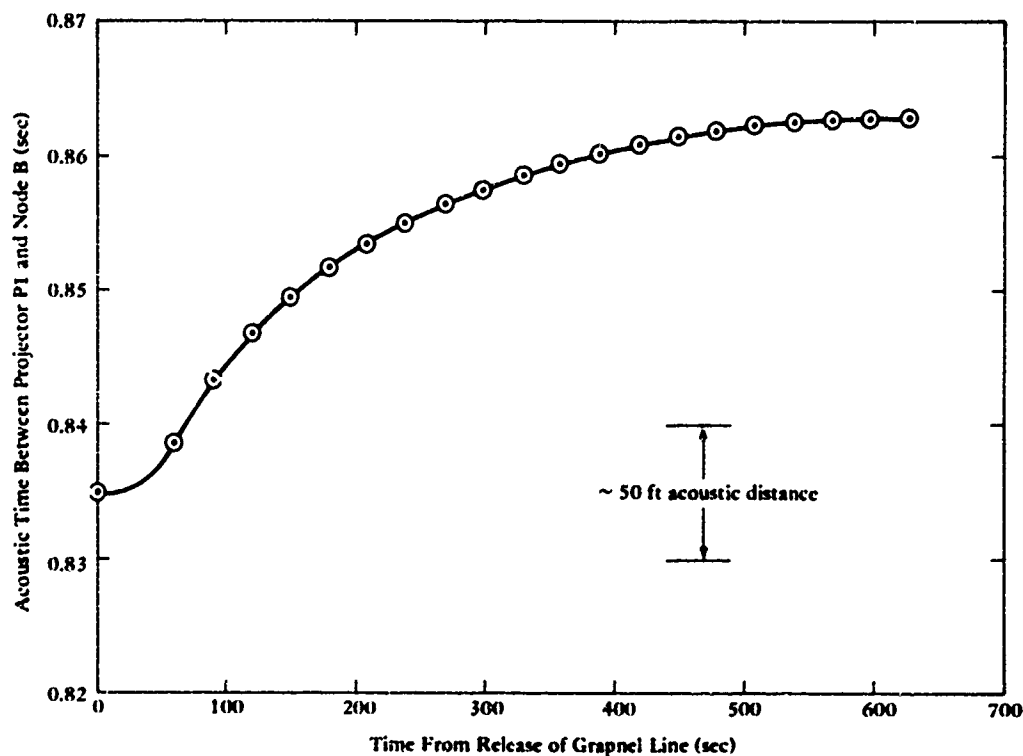


Figure 3-23. Acoustic time between projector P1 and node B during dynamic relaxation experiment.

analytical design program is presented in Chapter 6. As discussed earlier, position accuracy with the phase system and all three projectors operating exceeded the design goal for the positioning system.

Since good quality position data on the response of the structure to ocean currents had been collected, a bonus experiment was run. On 19 December 1975, some 15 months after the SEACON II structure was implanted, a dynamic relaxation experiment was performed. A grapnel was engaged with the structure at node buoy 2 (hydrophone B) apex of the delta. The delta was then pulled sideways in the direction of anchor A2, until it was displaced about 300 feet laterally (1,500-pound load on the grapnel line). The grapnel line was then released, and the position of node B was measured at 30-second intervals. Figure 3-23 is an example of the acoustic time data between projector P1 and the hydrophone at node B as the structure relaxed to its equilibrium position. The data appear to be of excellent quality and are being analyzed and reported on separately (Reference 3-4). At the start of the fourth relaxation test all of the

sensor stations on the delta went dead. It is believed that the ground connection to the mechanical wire at node A was broken by the tests.

#### Performance of Depth Measurement System

The depth measuring system provided very necessary data during the long period when projector P1 was inoperable. It also provided redundant data as a means of checking on the accuracy of the acoustic positioning system.

**Bias Errors in Depth Measurements.** The initial comparison of predicted depths to measured depths showed the measured depths of all nodes to be consistently shallower than the analytical predictions. The entire method for reducing the pressure sensor data was reviewed to determine if any discrepancies existed which might cause such a bias. One was located. As discussed earlier, the pressure sensors were calibrated in CEL's pressure facility. The vessel pressure was sensed in the vessel head, while the



sensors being calibrated were at a depth of 15 to 20 feet down in the vessel. This caused a 15-to-20-foot bias in the calculation of depth measurement. Using the zero pressure calibration data taken in air before the sensors were placed in the vessel removed the 15-to-20-foot bias.

Since this change did not make up for all of the discrepancy between measured and predicted depths, it was decided to obtain independent depth measurements acoustically. This was accomplished by stationing one vessel at the crown buoy to manually turn on the hydrophones while another vessel positioned itself over each of the acoustic nodes in turn and sent 14.5 kHz signals down. The difference in time between the first bottom reflection and the first surface reflection to reach a node gives an accurate measurement of twice the node depth. When the tide is taken into account, a depth corrected to mean low low water (MLLW) is obtained. Fairly good agreement was found between the depth determined with the new zero pressure data and the depth soundings. The depths of nodes A and C could not be measured acoustically because their hydrophones were not operating. However, B agreed to the nearest 1 foot, D within 2 feet, E within 14 feet, and G within 5 feet. Despite this agreement, the initial depth predictions were still somewhat deeper than the revised measured data showed. It was found later that the depth predictions were in error due to incorrect assumptions about penetration depths for anchors A1 and A2, as discussed earlier in this chapter.

**Random Errors in Depth Measurements.** Since the change in position of the structure (including its depth) follows a tidal cycle, one can provide insight into the random error of the depth sensor data by examining the variation in depth with time at a node sensor station. Figure 3-24 is a plot of typical data obtained from the depth sensors during low current velocity periods when the structure is fairly quiescent. From these data it appears the random error is generally about  $\pm 0.5$  foot or less. This exceeds the design criteria set up for the system. It is about twice as high as that claimed by the sensor manufacturer. This is reasonable because it represents the random error from two sensors in series since node F depth data are used to correct for tides. In addition node F moves vertically somewhat as discussed earlier.

**Acoustic Position Determination Using Redundant Depth Data.** During the period when all three acoustic projectors were operating, the depth data provided redundancy that could be used to assess the absolute accuracy of the entire positioning system. This involved not only the errors which exist in the acoustic position and depth measuring equipment, but the accuracy of the positioning data on the three acoustic projectors on the seafloor.

Figure 3-25 shows four x-y positions calculated for acoustic node D. The center position is determined by the acoustic ray distances from each of the projectors, P1, P2, and P3. Using these data, the calculated depth,  $z$ , is 430.7 feet, which is 3.3 feet less than that measured with the pressure sensor. The other three positions calculated with the measured depth,  $z$ , and two acoustic distances circle the position calculated solely from the acoustic data at a radius of about 5 feet. These are typical data which appear to indicate that the depths of the sensor stations are correct in an absolute sense within a few feet and the acoustic projector positions are correct within 5 to 10 feet relative to one another. Note that the above data indicate the magnitude of constant error or bias which should not be confused with the relative positioning accuracy over a period of days of  $\pm 1$  foot.

#### **Performance of Tension Measurement System**

Only two of the five tension cells survived the implant. Figure 3-26 shows two of the failed thin-walled tubes as they looked after the structure was recovered. The three failed cells were located on the delta arms, with the two undamaged cells located at each end of leg 1.3 which connected node A and the clump anchor. Based on the location of the failed units, it is strongly suspected they were overloaded during the removal of the flooded sensor canister from the delta arm between nodes A and B in Phase IV of the implant. For a short period the implant vessel was moored to the stretched-out delta, and its loading may have exceeded the 2,500-pound failure load for the cells. After Phase IV the load cell at the top of leg 1.3 always had higher tensions on it than any of the cells on the delta arms and yet it survived.

Because tension measurement was a backup to the acoustic position measuring system, its high failure rate did not seriously affect the validation

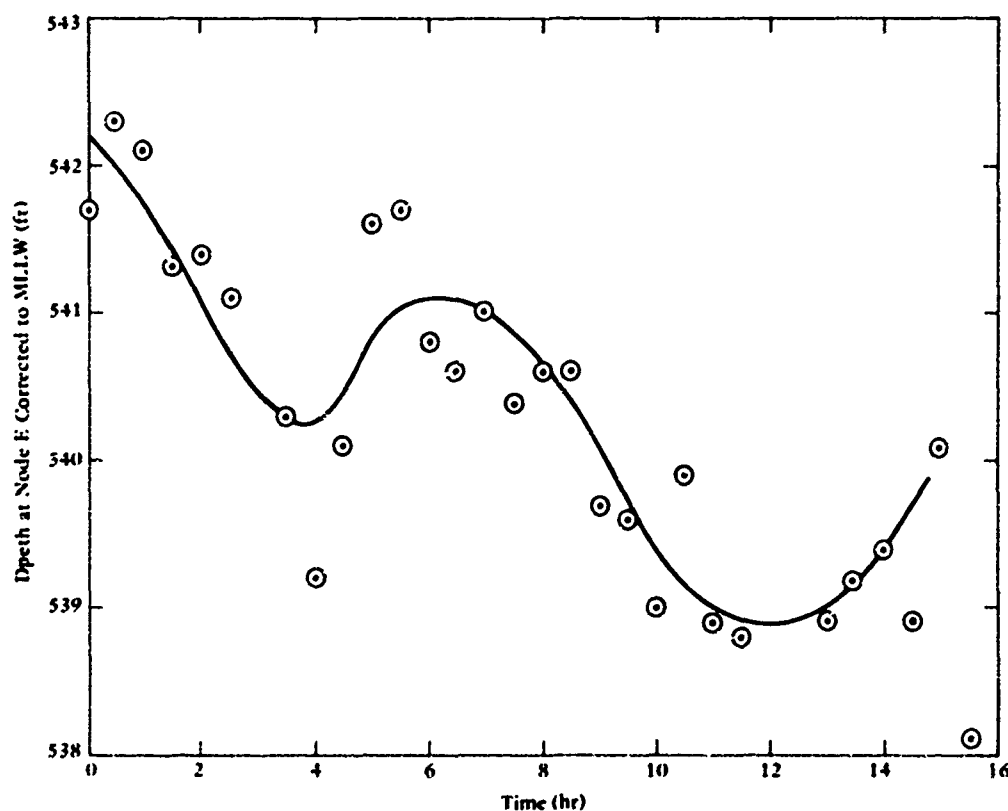


Figure 3-24. Depth measurements at node E over a 16-hour period during low current velocities.

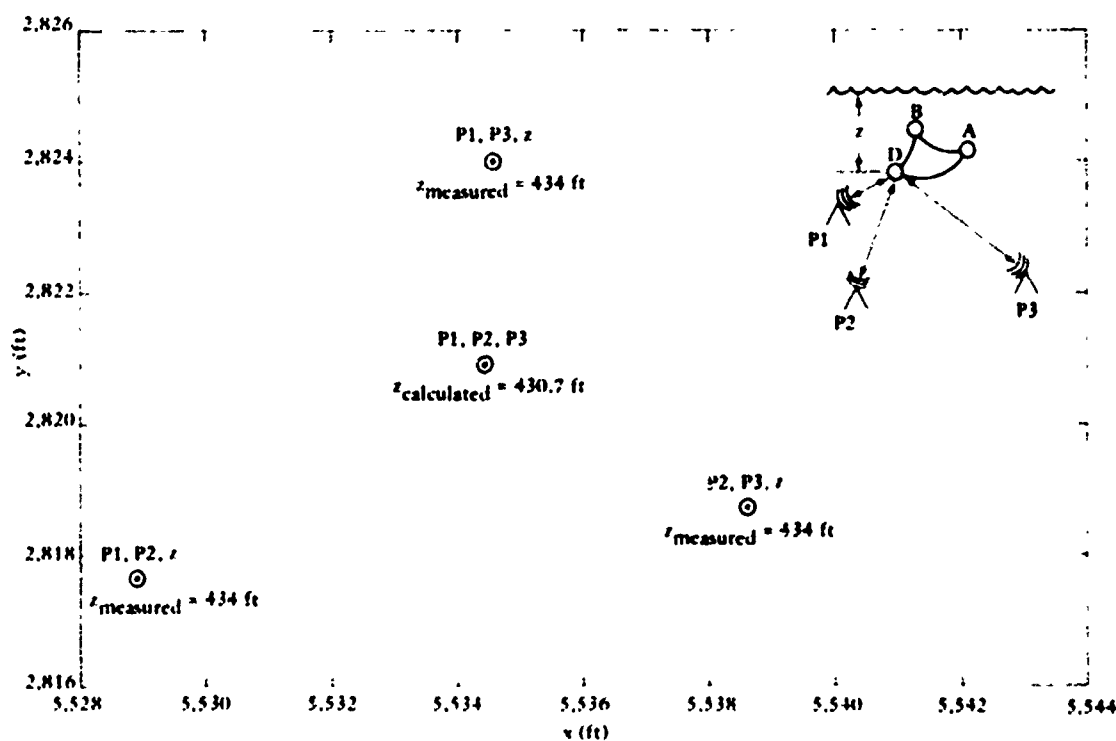


Figure 3-25. Comparison of positions calculated for node D using acoustic distances from three projectors (P1, P2, and P3) and depth,  $z$ .

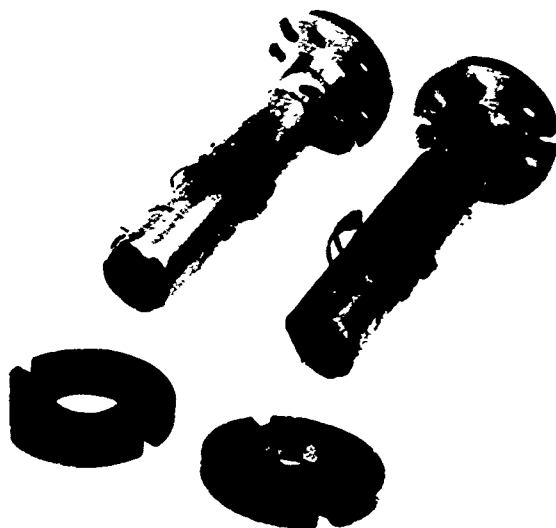


Figure 3-26. Instrumented tension links failed by overloading during implant operation.

experiment. The two units that did survive the implant worked well and demonstrated a good design for an in-line, undersea tension cell.

With only one of the three units at node A operating, there is no method for determining the absolute accuracy of the tension measurements. However, an idea of the quality and resolution of the tension data can be gleaned from data presented in Figure 3-27. Typical tension data from the cell located at the top of leg 1.3 at node A is plotted over a 36-hour period. As with the data from the other sensors the period of the cycles are tidal due to the character of the currents. From the curves it appears the random error is much less than the design goal of  $\pm 5$  pounds.

#### Performance of Power System

The RTG performed without problems for the entire 22-month implant period. The equipment even survived the shorting of the power leads to seawater at the crown buoy when the umbilical cable parted. The backup lead-acid battery was not used.

Some problems were experienced with the Ni-Cad battery pack in the crown buoy canister. On one occasion part of the battery circuit was shorted to the pressure case, draining the batteries and causing a loss of data. Also, periodically some bad cells were found and had to be replaced.

The mercury cells used in the distributed power system performed well during the 18-month period of active use.

#### FINDINGS AND CONCLUSIONS

1. The pulse-phase acoustic position measuring system proved capable of making position measurements with a relative accuracy over a period of days better than the  $\pm 1$ -foot design goal.
2. The precise behavior of the acoustic signals used in the positioning system was misjudged, and thereby presented a serious and time-consuming obstacle to overcome in order to obtain good quality data.
3. Despite major obstacles encountered, sufficient position data of high quality were collected to meet the goals for validating the computer program to the desired level of accuracy.
4. The depth measuring equipment met the design goal for accuracy and proved to be a valuable adjunct to the acoustic positioning system.
5. The tension cell developed by CFI for in-line use in underwater cables produced good quality data which met or exceeded the design goal for accuracy and sensitivity. However, the tension-measuring member proved so fragile that only two of the five cells survived the implant.
6. The electronics in the underwater sensor stations proved to be highly reliable.
7. The crown buoy electronics proved less reliable, probably due to the severe handling and corrosive environment experienced during numerous trips from laboratory to harbor to site and back. The failure rate of the electronic equipment in the crown buoy canister was so high that it was unable to meet the design goal of 1 month unattended implant.
8. The power system, especially the RTG and mercury batteries, proved to be very reliable.

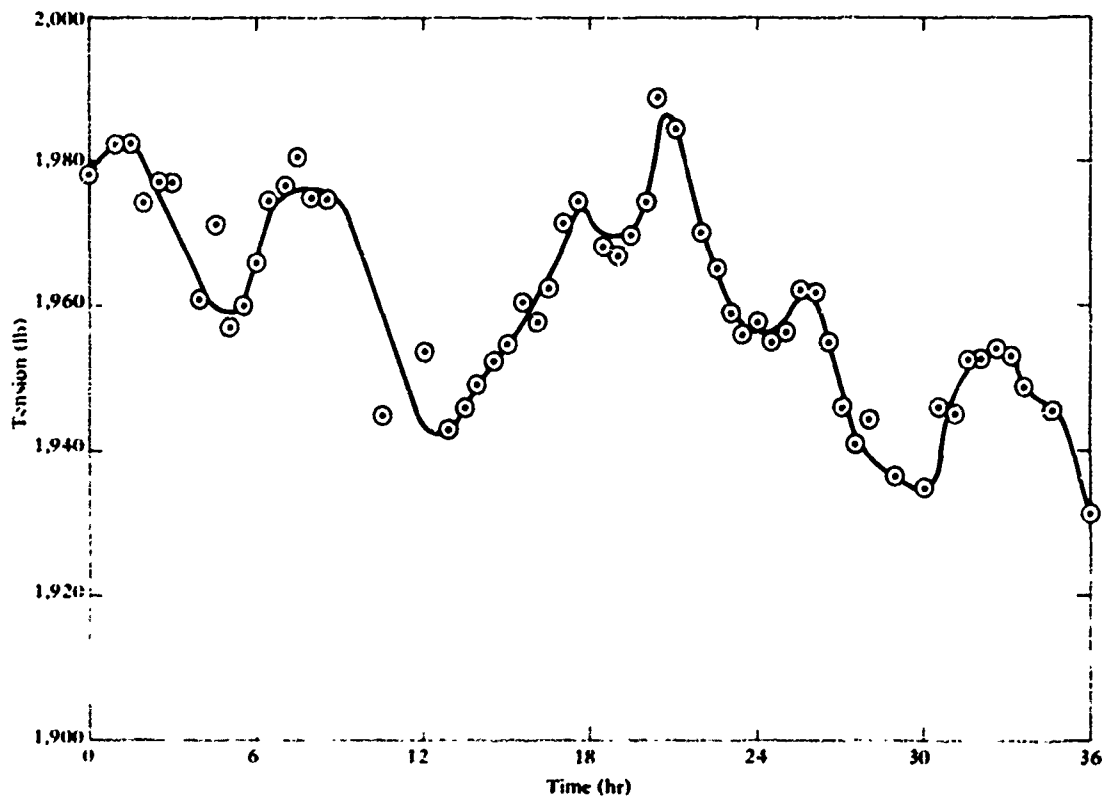


Figure 3-27. Tension variation at top of leg 1.3 at node A during 36-hour period.

9. The analysis of the redundant position data indicates the measured acoustic projector positions were accurate to within 5 to 10 feet relative to one another.

10. The position measuring system met the design goal of taking position data at 30-second intervals. It was also successfully used to collect data in a dynamic relaxation experiment performed with the SEACON II structure.

2. The pulse-phase acoustic position measuring system developed by C.E.I. is recommended for use where precise three-dimensional position measurements are required.

3. The tension cell developed by C.E.I. provides a good design for a reliable undersea unit for measuring cable tensions. To prevent premature failure of the tension link, either a larger factor of safety should be used in designing the link or some method should be provided to prevent overloading the link.

## RECOMMENDATIONS

1. In operations such as SEACON II, in which complex and precise electronic controls and measurements are made on undersea hardware, the control and recording should be done from either a shore station with a cable to the undersea hardware or from a stable platform with good lab space moored over the undersea site.

## SECTION 4 - CURRENT MEASUREMENT SUBSYSTEM

### DESIGN CRITERIA

The parametric analysis presented earlier confirmed current measurement accuracy to be one of the two most critical parameters in the program validation effort. As shown in Table 3-2, an accuracy of  $\pm 1.0$  cm/sec for velocity and  $\pm 4$  degrees for direction corresponds to an equivalent accuracy of  $\pm 0.10$  for the pacing parameter,  $C_d$ . This, along with other considerations, were used to establish the following design criteria:

- The accuracy of the current measurement system must be  $\pm 1$  cm/sec for velocity and  $\pm 4$  degrees for direction in the range of 5 to 35 cm/sec with a current velocity threshold of 2 cm/sec or less.
- Sufficient measurements must be made over the area occupied by the structure to determine areal variability of current speed and direction.
- Sufficient measurement stations must be provided to define the current depth profile from 400 feet to the bottom within system accuracy requirements.
- The current meters must be self-contained, be capable of recording current measurements at least once every 10 minutes for a minimum installation period of 2 months, and have a timing accuracy of  $\pm 2$  seconds/24 hours.
- The current meter moors must be designed to be easily and reliably deployed and recovered.
- The top of the current meter strings must be sufficiently deep to not be significantly affected by ocean surface conditions at the site. A surface buoy must not be used to mark their position.

## CURRENT METERS

### Selection and Description

Electromagnetic-, acoustic-, and rotor-type meters were all investigated to determine the best sensor type for high accuracies at low velocities. In the state-of-the-art at that time (1973) the rotor-type meter appeared to best meet the requirements.

In discussions with various users of current meters, the Aanderaa Recording Current Meters RCM-4 and RCM-5 were recommended as being the most accurate and, most of all, the most reliable. Based on other user information, CEL experience, and a survey of the market, a commitment was made to use Aanderaa meters for the bulk of current measurements during the SEACON II experiment.

The Aanderaa instruments (Figure 3-28) are designed to measure water current speed, direction, and temperature with options that include depth (pressure) and conductivity. These parameters are measured and recorded according to a preprogrammed sampling scheme.

Current speed is sensed by a Savonius-like rotor that drives a potentiometer via a magnetically coupled follower and gearbox. Current direction is sensed with a vane and fluid-damped magnetic compass. When the compass is to be read, a contact is clamped against a wire-wound resistance ring. Measurement of each sensor output is achieved by sequentially switching each output into an automatically controlled bridge-balancing circuit, the heart of which is a rotary encoder. The digitized data are recorded on magnetic tape. The sampling interval is controlled by a solid-state timer driven by an oscillator that is controlled by a quartz crystal. The timer accuracy is specified to be  $\pm 2$  sec/day. Several sampling intervals are available with 10 minutes being standard.

### Evaluation and Calibration

Due to the stringent accuracy requirements for the SEACON II current measurement system, CEL

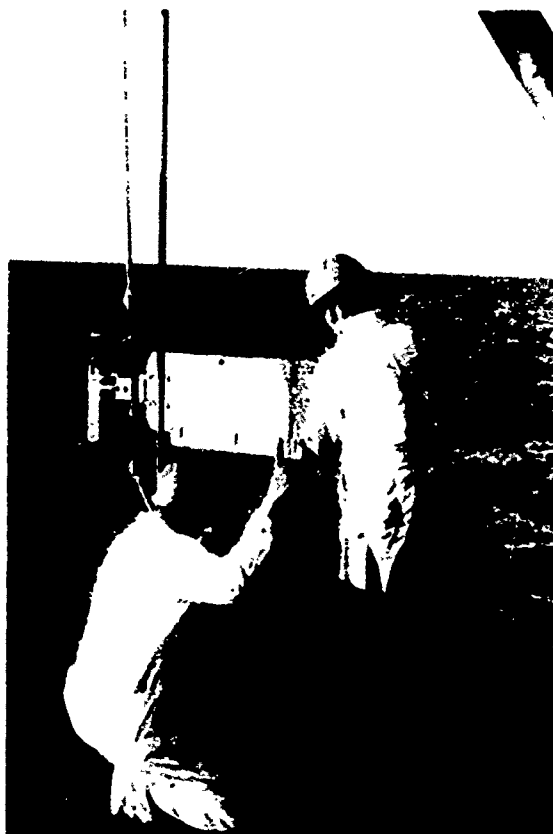


Figure 3-28. Aanderaa current meter being installed. Speed rotor is located on top of pressure housing. Vane aligns with current to provide direction reference.

decided a thorough evaluation of the Aanderaa meter was required. CEL requested the U.S. Department of Commerce, National Oceanographic Instrumentation Center (NOIC), Washington, DC [3-5], to determine the speed and direction accuracies for the Aanderaa meters, especially at low current velocities (0 to 35 cm/sec). NOIC performed an evaluation, and it issued an Instrument Fact Sheet [3-5] that contains a summary of the test results.

The results show that, in the low speed range (0 to 50 cm/sec), the nonlinearity was  $\pm 0.8$  cm/sec. In addition, the sum of a quantization error and potentiometer error at the 10-minute sample time had a worst case total of 1.6 cm/sec with a 6,000:1 rotor gear ratio. Because the current velocities at the SEACON II site were in the lower half of the low

speed range, it was decided to use a 1,200:1 gear ratio, which significantly reduces the errors due to quantization and potentiometer linearity. With the lower gear ratio it is estimated the total error in speed in the range of specific interest to the SEACON II experiment to be about  $\pm 1.0$  cm/sec.

The compass evaluation showed a nonlinearity of  $\pm 2.5$  degrees, which can be corrected by individual calibration of each compass and a nonrepeatability of  $\pm 2.8$  degrees. Added to this error in compass direction is the error in vane alignment with the current at various current velocities. This error ranges from about  $\pm 7.5$  degrees at 5 cm/sec to  $\pm 4$  degrees at 10 cm/sec to  $\pm 1$  degree at 35 cm/sec. Current speeds that significantly displace the SEACON II structure are above 10 cm/sec; so, in general, the direction inaccuracy of a meter with a calibrated compass in the SEACON II flow speed regime could be expected to be less than  $\pm 6.8$  degrees.

To avoid the error penalty associated with compass nonlinearity, a compass calibration facility was set up at CEL, and all Aanderaa meters were calibrated at 10-degree compass intervals.

#### MOOR DESIGN

In order to detect and measure any areal variability in the current speed and direction at the SEACON II site, the decision was made to surround the structure with three current meter strings. Each string was to be located approximately 700 feet out from the center of each of the three delta arms, which placed the strings about 1,600 feet apart.

There was little experience to draw on in determining the depths at which meters should be placed to accurately define the current profile and to avoid missing any shear currents that might exist. Due to the meager data collected on currents during the site investigation phase, it was not known how much the current velocities changed with depth. However, it was known that the measured velocities at the 1,050-foot depth were as high as those at 500 feet, and it was suspected that the velocities would drop off sharply below the basin sill depth of 2,400 feet. To obtain more information on the profile at deeper depths as well as to check out a new moor design, a current meter string (Figure 3-29) that included

meters at 1,450 and 2,200 feet was installed. Unfortunately, when the string was recovered, it was found that the velocity data at the 2,200-foot depth were no good. The velocities at the 1,450-foot depth, however, were found to be as high or higher than those at the shallower depths.

Another factor went into determining the most efficient distribution of meters in the vertical direction. The buoys and delta cables produce a large percentage of the total drag force on the structure. In addition, the structure response is much like that of a cantilever beam; a unit of force produces a larger displacement the higher up it is applied on the structure. From this information it was obviously important that the currents at the delta elevation be well monitored by meters. Below the 500-foot level meters were spaced approximately in a logarithmic fashion, with spacing increasing as depth increased.

After the structure was installed, three strings containing 19 meters were implanted. Since only 13 Aanderaa meters were available to CFI, six other meters of various types and vintages were used. The older meters were concentrated at the lower levels, which were considered less critical, in case they failed.

The moor design used during the structure implant was based on the successful design evolved during the site investigation phase and is described briefly in Chapter 2. The major change was to remove the surface spar buoy and to place the top subsurface buoy approximately 400 feet below the surface to decouple the moor from surface action.

To increase the probability of a moor releasing on acoustic command, dual AMF acoustic releases were used between the anchor and the bottom redundant buoyancy. A dual release bracket was developed so that both releases would be recovered if either of the acoustic releases was activated. The bracket, Figure 3-30, uses a lever arm arrangement so that only a small percentage of the load is carried by the releases. When either of the releases is activated, the lever arm falls down, releases a captured pin, and allows the shackle to fall free of the bracket.

To aid in locating the moor after it surfaced, a Xenon flasher and radio direction finder transmitter were attached to the top buoy.

Two of the three strings were made of 1/2-inch-diameter braided dacron designed for very low

stretch; the third was made up of 1/4-inch-diameter wire rope. The two types of mooring lines were used in order to investigate the effects of dynamic behavior of different moors on meter performance. The moors were designed for deploying the anchor first because of the need to precisely control the final implanted position of each string.

#### VERIFICATION OF IN-SITU CURRENT MEASUREMENT ACCURACY

Two methods were devised to verify and improve accuracy of the in-situ current measurements. Redundant meters were located at the most critical depths to provide a crosscheck between meters. Averaging these redundant data also improved overall accuracy for the current measurement system.

A second method used to verify the accuracy of the current meter measurements was the tracking of a neutral float device (Figure 3-31). A submersible transponder was incorporated into a device that could be made neutrally buoyant at a predetermined depth. The buoyancy of the device was adjusted by increasing or decreasing its weight so that it would free-fall until the buoyant force of the object was opposed by an equal gravitational force at the desired operating depth. The device was allowed to drift with the current stream through the area occupied by the structure and the current meter strings, and its movement was monitored by the acoustic transponder navigation equipment at the SEACON II site. Then, by an acoustic command that causes a ballast weight to release, the device was returned to the surface for recovery.

Buoyancy was provided by two titanium spheres capable of operation to pressures in excess of 5,000 psi. These spheres were coupled together and supported the negatively buoyant components of the devices. An AMF model 322 recoverable acoustic transponder, which was set up for submersible tracking in an acoustic navigation net, permitted the neutral float device to be accurately tracked. The transponder also provided the primary means for recovery with its acoustic release mechanism.

An alternate release mechanism was included on the float as a backup for the acoustically activated squib release on the AMF model 322. The alternate

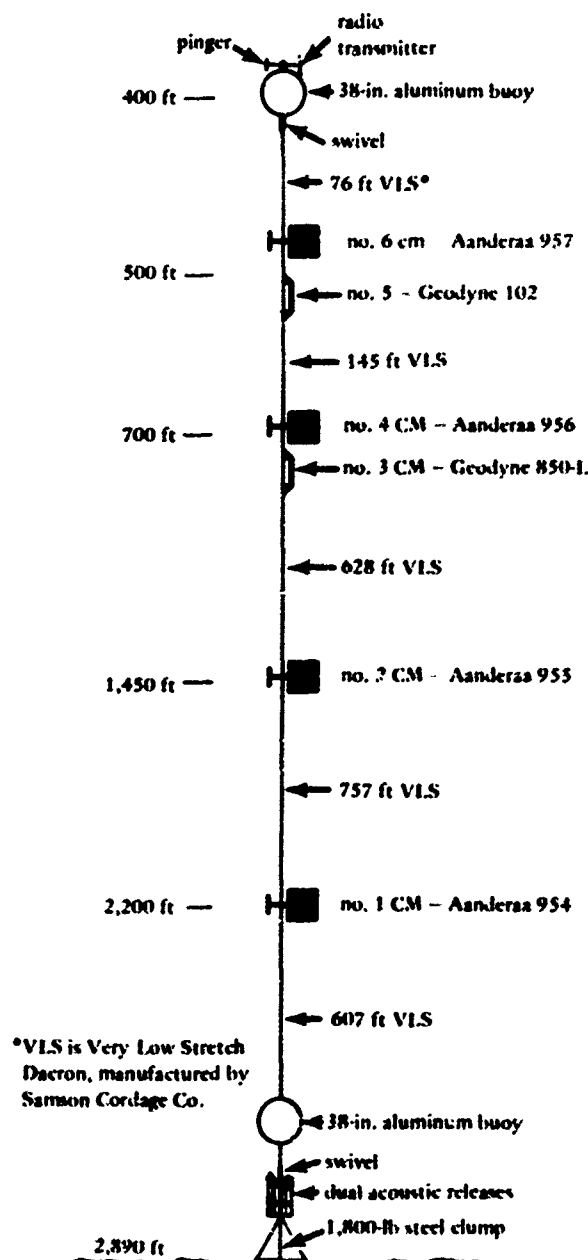


Figure 3-29. Current meter string installed to evaluate new moor design prior to SEACON II implant.

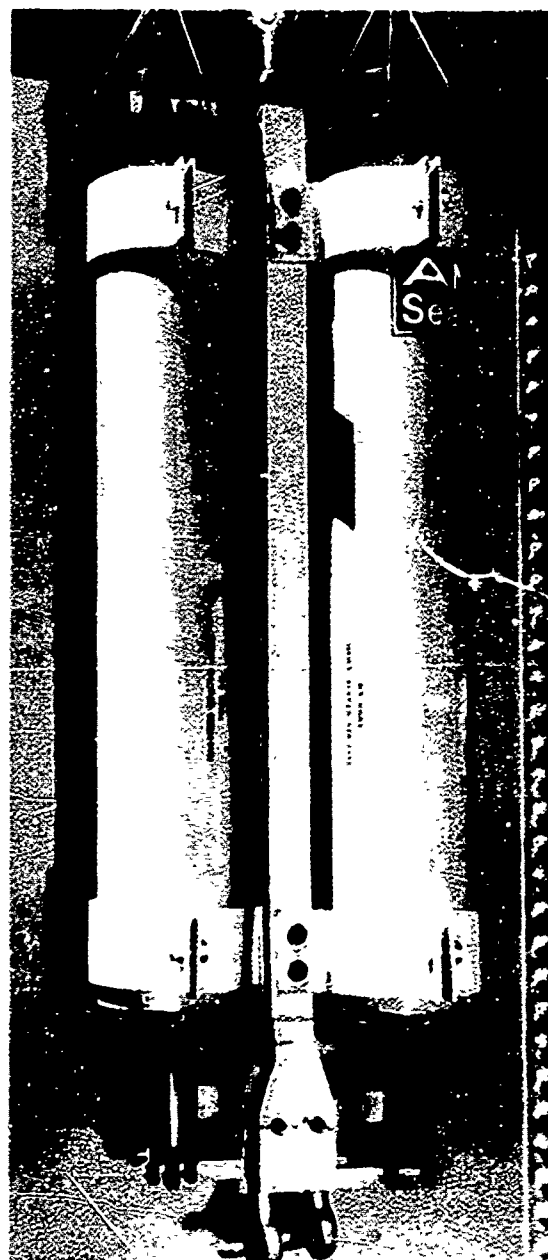


Figure 3-30. CF-1 developed dual release bracket, designed to carry majority of load below releases.



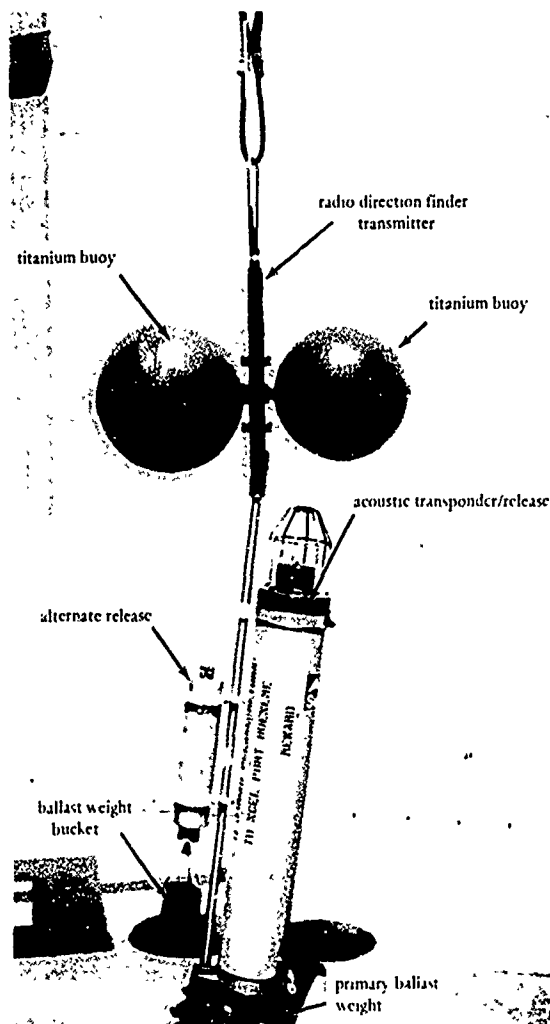


Figure 3-31. Neutral float device developed to measure currents in-situ.

release was a timed device which activates the firing circuit for an explosive bolt at a preset time. The time may be set from 0 to 12 hours at 15-minute increments. Should the primary release mechanism fail, the float is tracked by acoustic methods until the preset time or the alternate release has elapsed; at this time an explosive bolt is fired to release a ballast weight, which allows the float to return to the surface.

The ballast weight, which was made of steel, consisted of two separate parts. About half of it was attached to the primary release on the transponder. The remainder was attached to the alternate release mechanism. Fine adjustment of the buoyancy of the float was accomplished by adding or removing lead shot from the weight bucket on the alternate release device.

A submersible RDF transmitter was attached to the device to assist in locating the float after it surfaces. This transmitter activates just prior to reaching the surface and can be tracked with a hand-held direction finder.

To achieve neutral buoyancy at any depth, the device must first be made neutrally buoyant at the surface at 0 psig, and then adjustments to the device's net weight must be made to correct for the compressibility of the device and for the changing water density as a function of temperature, salinity, and pressure. The effects of temperature and salinity are determined by taking an STD profile at the site and figuring density from a T-S diagram. The effects of increasing hydrostatic pressure were determined by measuring the changing weight of the device as it hung on an instrumented cantilever beam inside a pressure vessel.

## RESULTS AND DISCUSSION

### Velocity and Direction Accuracy

Figure 3-32 is a plot of typical current speed versus time records for two meters located at a depth of approximately 500 feet and separated a distance of 3 feet vertically. The measurements agree with one another generally better than the  $\pm 1$ -cm/sec accuracy goal for the measurement system. Figure 3-33 is a plot of direction readings for these two meters during

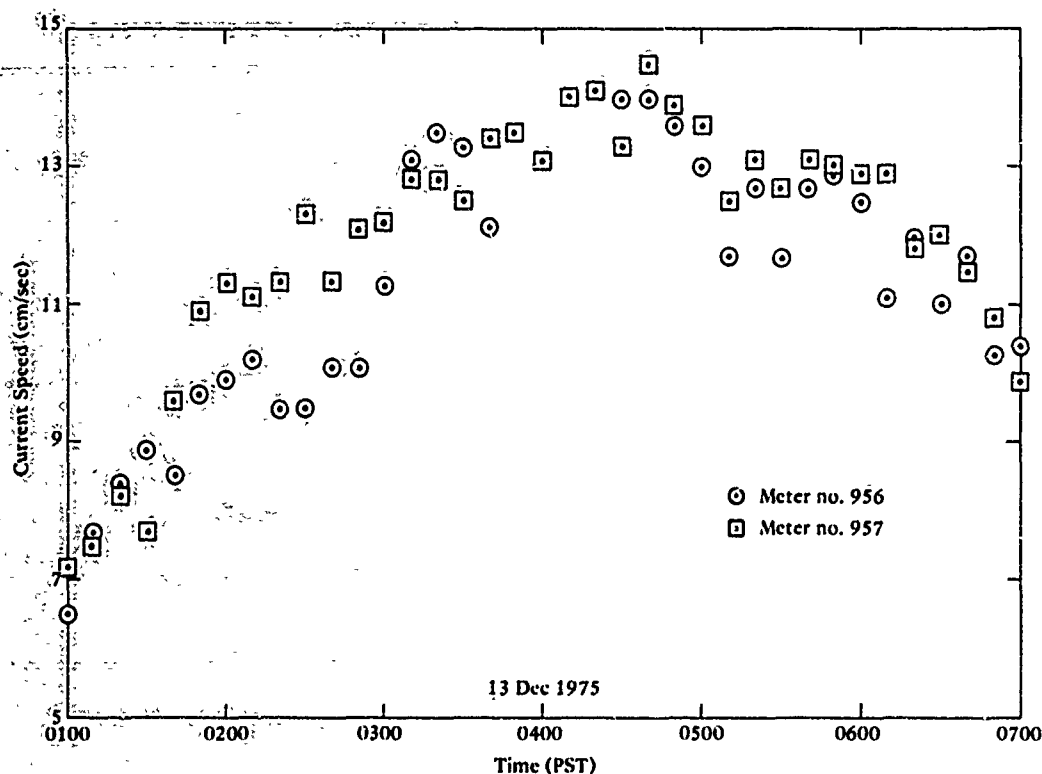


Figure 3-32. Comparison of typical current speed data measured by two Aanderaa meters separated 3 feet vertically at a depth of 500 feet.

the same time period. The direction readings generally agree within about  $\pm 3$  to 4 degrees, which is about equal to the design goal for the measurement system.

Good agreement between two nearby meters, of course, does not assure they are measuring speed and direction accurately. Something in the system, such as moor motion, could apply a large constant error or bias equally to both meters. In order to verify the meter readings, the neutral float was passed through the general area where the current meter string was located. Figure 3-34 shows the trackline for one of the neutral float passes. Note that, at its closest point, it was about 2,500 feet laterally from the current meter string. The float started at a depth of about 383 feet and generally edged deeper as it crossed the site, reaching a depth of 454 feet just before it was recalled to the surface. Figure 3-35 compares the speed and direction data from the meter at 400 feet with those from the neutral float. During the period

when the float was close to 400 feet, the speed readings agree within about 3 to 4 cm/sec in a total velocity of about 25 cm/sec. Direction measurements agree within 10 to 15 degrees. Neither the level of agreement between the neutral float and meter data nor the location where the data were taken are close enough to be able to certify the exact accuracy of the meter data. However, considering the distance between the measurements, the agreement is quite good and would appear to indicate that there are no factors at work seriously biasing the meter data. Based on these results it appears that individual meter accuracy in the ocean is about  $\pm 1$  cm/sec for speed and  $\pm 5$  degrees for direction at velocities above 10 cm/sec.

#### Areal Variability at the Site

Three current meter strings were placed around the structure to determine whether large variation of

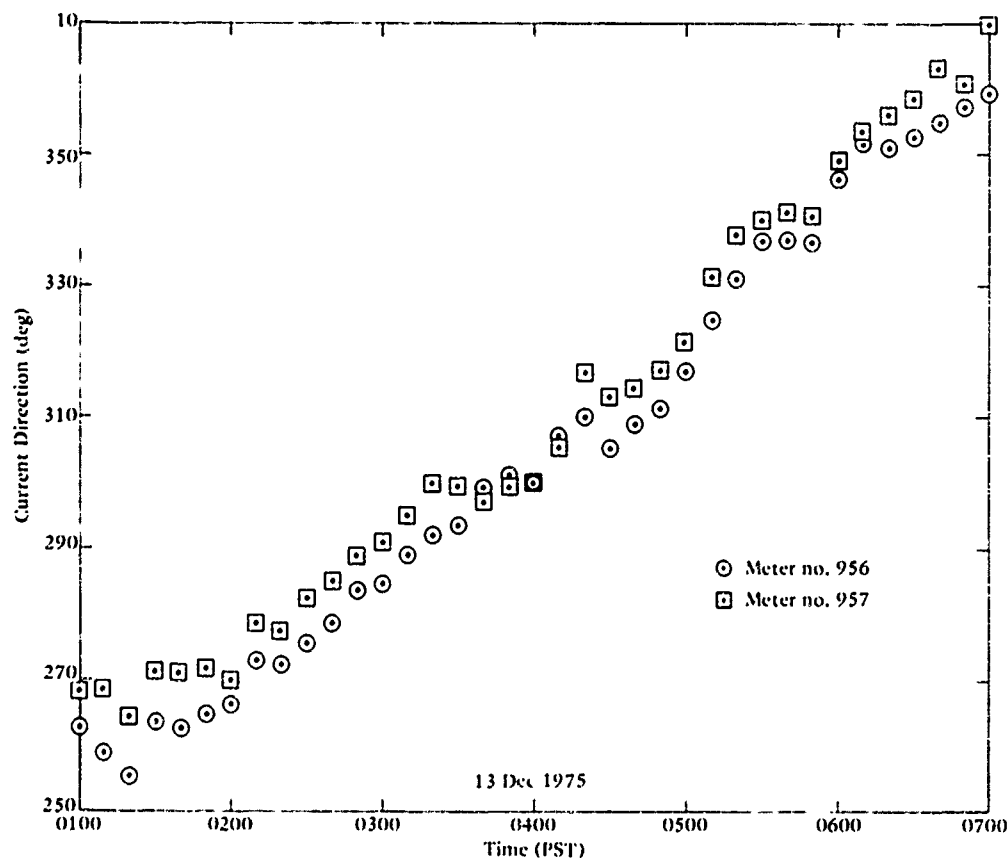


Figure 3-33. Comparison of typical current direction data measured by two Aanderaa meters separated 3 feet vertically at a depth of 500 feet.

currents over the area existed. Figure 3-36 shows typical current speed data collected by three meters at a depth of 500 feet on the three separate strings located approximately 1,600 feet apart. Generally, the range of readings is about  $\pm 1$  to 1.5 cm/sec over a 6-hour period. This is about twice the variation that was seen on the two meters adjacent to one another on a single string; this appears to indicate some small areal variability in the speed of about  $\pm 0.75$  cm/sec in the vicinity of 10 to 12 cm/sec currents. The direction variation (Figure 3-37) when the velocity was above 10 cm/sec appears to be about  $\pm 5$  degrees, slightly more than the previously described results with two adjacent meters. However, data from the two adjacent meters on string no. 2 (Figure 3-37) agree within  $\pm 1$  to 2 degrees.

Based on these results it was concluded that areal variability at the site for both speed and direction was small. It was decided a more productive use of the meters would be to increase the number on a single string to better define the vertical profile at the site. In addition the total number of meters could be cut; this allowed exclusive use of the Aanderaa meters, which greatly simplified the data reduction process.

Starting with the third set of current meters installed after the structure was implanted, only one string containing from 10 to 11 Aanderaa meters was used. Because of the major effect of the currents acting high up on the structure, the meters were generally spaced 100 feet apart from 400 to 900 feet and then placed in a logarithmic spacing to the deeper depths. Meters were doubled up at the 400- and

Table 3-4. Current Meter Performance

Implant No.	No. of Strings	No. of Days Implanted	No. of Aanderaa Meters	No. of Meters Collected Good Data	
				Velocity	Direction
1	1	33	4	3	4
2	3	74	13	11	12
3	3	79	13	11	12
4	1	64	10	9	10
5	1	49	10	9	9
6	1	63	11	9	9
7	1	42	11	8	9
Totals	11	404	72	60 (83%)	65 (90%)

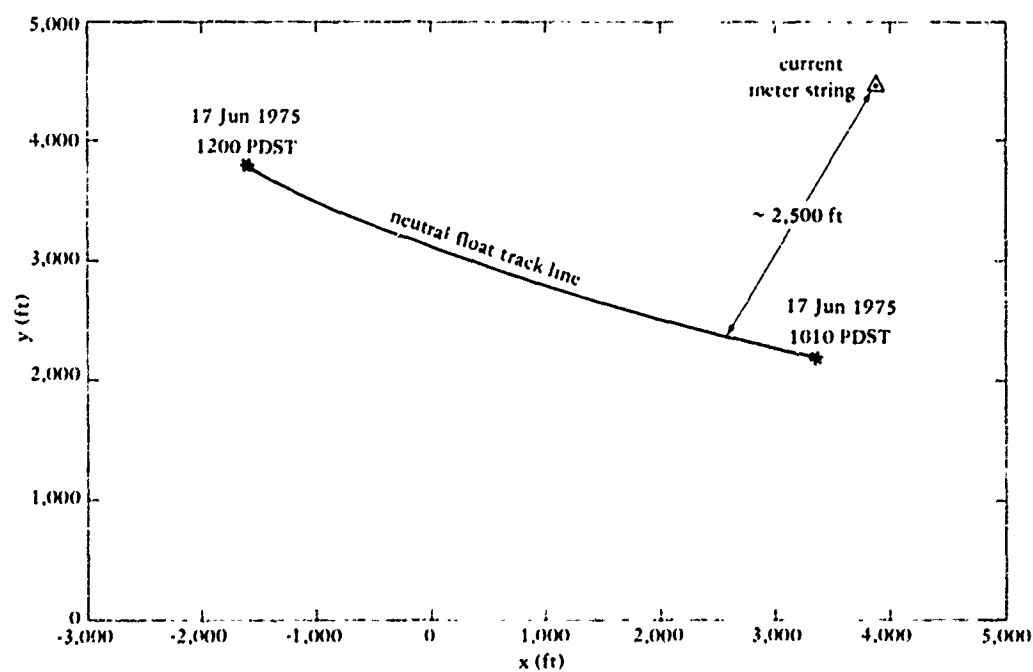


Figure 3-34. Track of neutral float passing through SFACON II site at a depth ranging from 371 to 466 feet. Track line is in acoustic transponder navigation system coordinates.

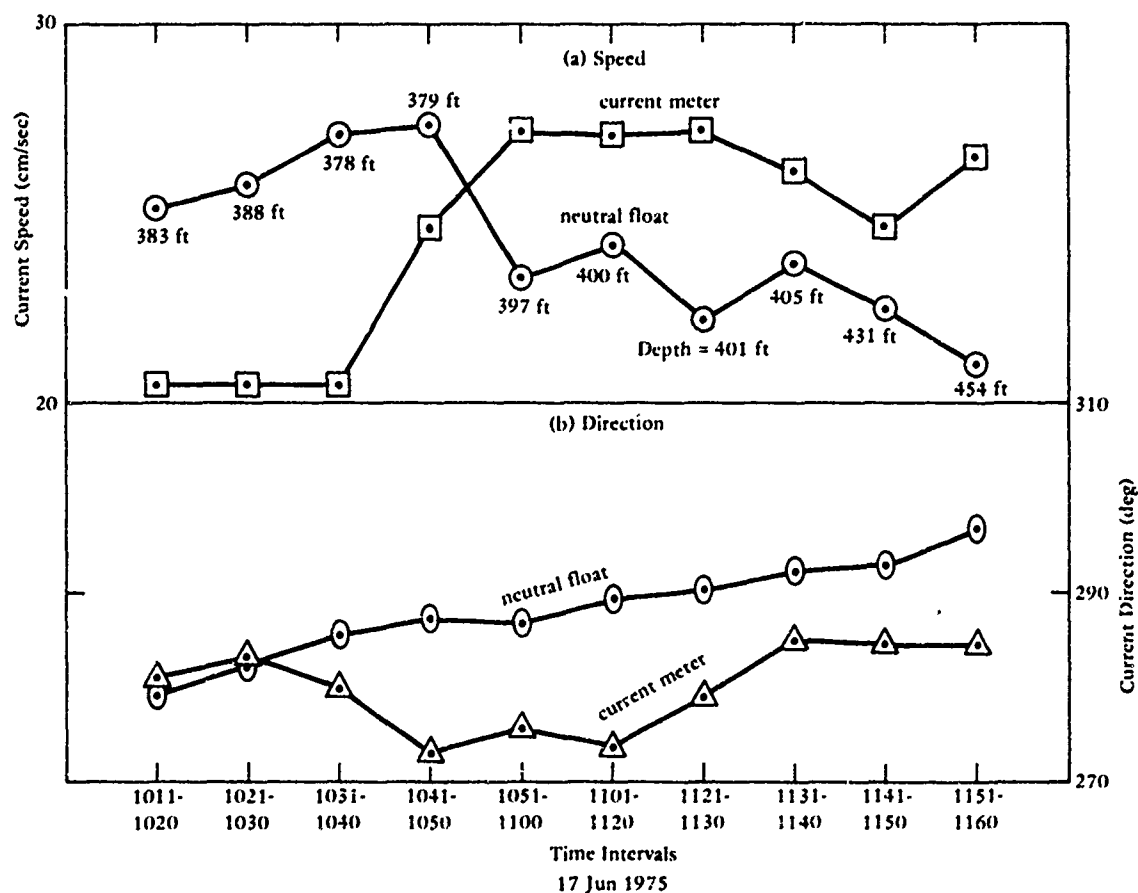


Figure 3-35. Comparison of current speed and direction determined using neutral float running between 378 and 454 feet deep, and Aanderaa current meter at a depth of 400 feet

500-foot depths to insure data recovery at these very critical depths and to provide redundant readings to increase accuracy of the measurement system.

#### Meter and Moor Performance

The primary factor in meter performance is how much of the time is good data being collected. Table 3-4 shows the number of Aanderaa meters installed and the number that collected good velocity and direction data during each of the seven implants. Good velocity data were obtained from 83% of the meters installed, with good direction data from 90% of the meters. Compared to past CHL experience as

well as that of many other current data collectors, this is a very good average. As reported in Chapter 2, good current data were collected from only 43% of the meters installed during the SEACON II site investigation phase.

Only two significant problems were encountered with the Aanderaa meters. One was a corrosion problem, and the other was in getting the tension properly adjusted for the data tape take up spool.

After the third implant the nickel plating on the cases was found to be peeling off, and the case material was corroding. To correct this problem the remaining plating was sandblasted off the case exteriors, and an epoxy paint system was used to

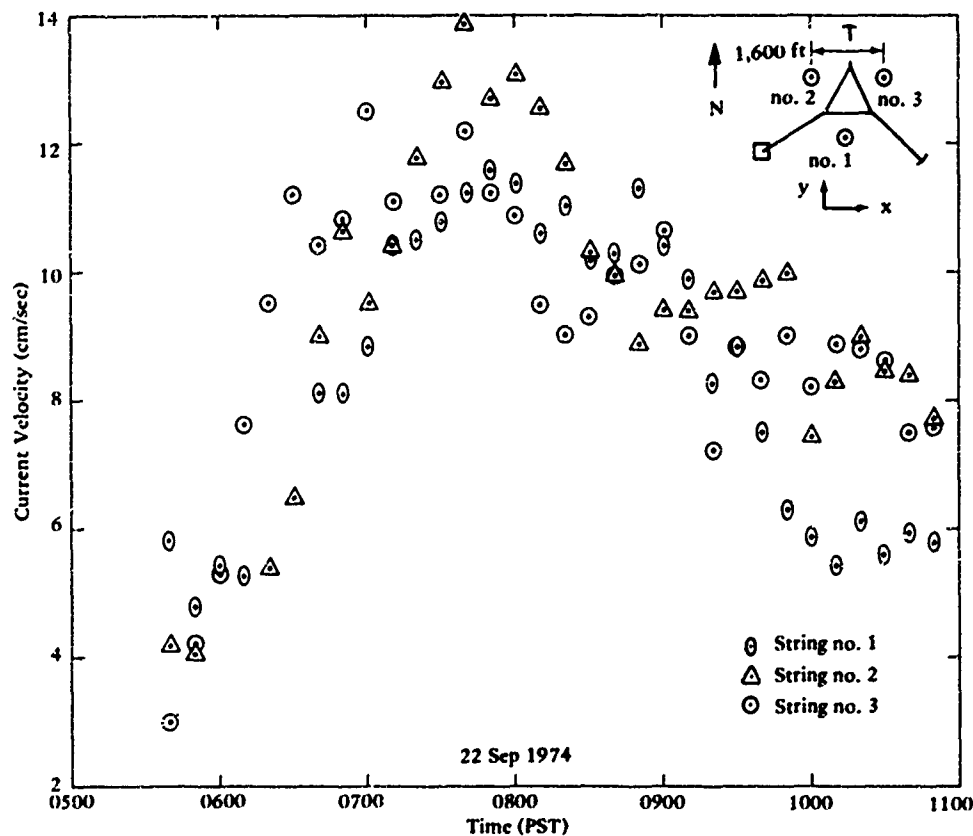


Figure 3-36. Current velocity versus time from three meters at a depth of 500 feet spaced approximately 1,600 feet apart laterally.

protect the cases. This worked well, and, after four additional implants, the cases were still in good condition.

The spool tension problem was found after data were reduced from the first implant. The tensioning was modified to correct the problem.

The moor design worked very well. All 11 current meter strings installed were successfully recovered. The backup release had to be employed on two of the 11 strings recovered. None of the buoys or meters flooded. The implant and recovery operations were accomplished very efficiently from CEL's LCM-8 boat. Typical time required to install the 2,500-foot-high moor with 10 or 11 current meters was 2 hours. Approximately 1-1/2 hours were needed to recover the moor. By using the ATNAV positioning system,

no problems were experienced in positioning the moor to avoid entanglement in the structure.

#### Neutral Float Performance

The neutral float, which performed remarkably well, provided good current data at the SEACON II site for comparison with the recording current meter data. The only significant problem experienced was in getting the device to the exact depth desired. Typically the device became neutrally buoyant some 20 to 50 feet above or below the target depth where a meter was located. This made it difficult to compare velocities measured by the two techniques. The worst case was when the device stopped too shallow; at least some comparisons could be made if the device

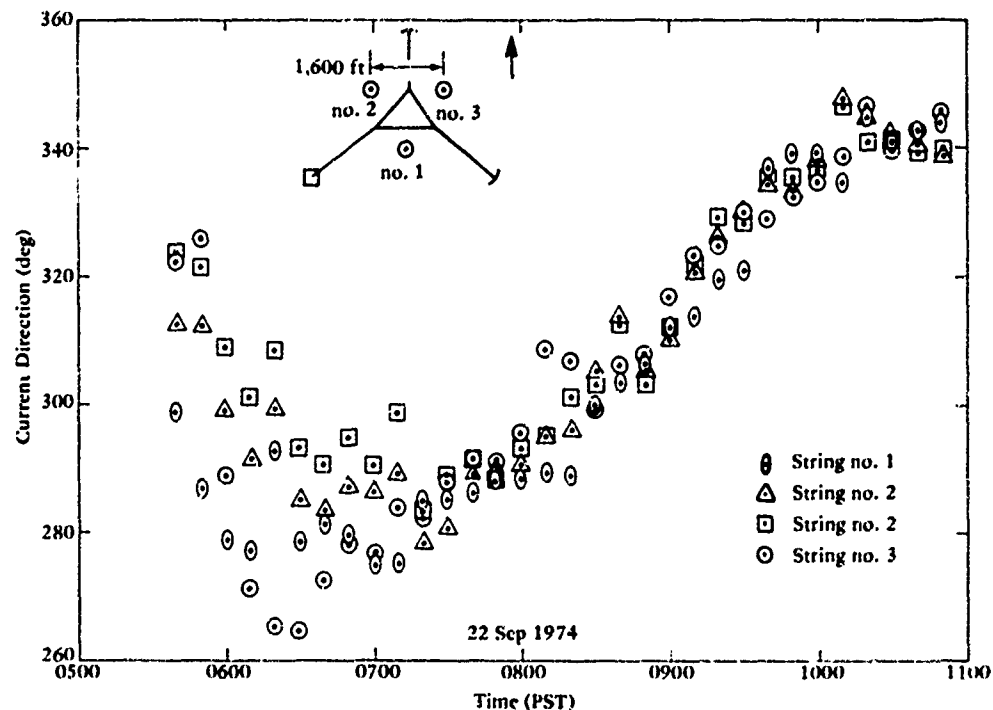


Figure 3-37. Current direction versus time from four meters at depth of 500 feet.

passed through the target depth, as occurred in the run presented earlier.

In seven runs made with the device, no significant problems occurred with the hardware. The primary release method worked each time, and recovery on the surface was routine using the transponder and radio positioning systems on the device.

#### FINDINGS AND CONCLUSIONS

1. It appears the speed measurements for the individual meters are accurate to  $\pm 1$  cm/sec and the direction measurements are generally accurate to about  $\pm 5$  degrees when speeds are above 10 cm/sec.

2. The areal variability at the site appeared to be on the order of  $\pm 1$  cm/sec for speed and  $\pm 3$  to 5 degrees for direction when speeds were above 10 cm/sec. This negated the need for three current meter strings.

3. It is believed the system accuracy meets or approaches very closely the desired accuracy of  $\pm 1$  cm/sec for speed and  $\pm 4$  degrees for direction. Situations where the system probably does not meet this level of accuracy are when significant shears occur between meters (as is discussed in Chapter 5) and on direction measurements when the speed is below 10 cm/sec.

4. The Aanderaa meters along with the moors that used a CEL-developed dual release bracket and AMF acoustic releases performed very reliably. All 11 of the moors were recovered, and the backup release had to be used only twice. The meters collected good velocity data 83% of the time and good direction data 90% of the time.

5. The neutral float device operated well and provided a means for calibrating the current meters in-place. However, difficulty was experienced in getting the device to float at the precise depth desired.

## RECOMMENDATION

The successful current moor design techniques, which incorporated redundant buoyancy, redundant releases with a refined design for a dual release bracket, and reliable meters, such as the Aanderaa RCM-4 or RCM-5, are recommended for use in all instrument moors where high reliability is required.



## CHAPTER 4

### IMPLANT OPERATIONS

Implant of the SEACON II structure began with the installation and survey of the acoustic transponder navigation system on 30 July 1974 and was completed approximately 6 weeks later on 12 September 1974 when the current measurement system was installed.

#### SECTION 1 - DESIGN

##### CRITERIA

The following criteria were established for designing the implant procedures to insure a highly reliable, flexible, safe, and ultimately successful sea operation would occur:

- Implant should be from a single ship to avoid difficult communication and coordination problems inherent in a multiple-ship operation.
- Implant operations and equipment must be designed for a maximum sea-state-3 condition.
- A multiphased installation plan with convenient stopping points must be developed so that the sea operations could be conveniently interrupted and the portion of the system already installed protected should adverse weather or equipment problems occur. Each phase should be able to be accomplished in less than one day and be reversible in order to repair equipment if problems occur.
- The phases should be designed so that they could be combined for more efficient operation in event of good weather and no equipment problems.
- At-sea electrical connections and splices should be minimized. Preassemble the electrical system in the largest assemblies feasible, and perform environmental testing on these assemblies before implantment.

- A means for monitoring and testing the electrical system during implant must be provided so corrective measures can be taken, if necessary, before proceeding to successive phases.
- The implant procedures must permit optimum positioning accuracy.
- The implant procedures must allow realistic at-sea training and practice to be conducted.
- Safety must be emphasized in the implant procedures.

##### CONCEPTS

Based on the outline of implant criteria, several implant concepts were formulated in February 1973. The selected concept was integrated with the system design to insure the hardware design and installation plan would be compatible. Between February 1973 and July 1974, when the final operations plan was issued, six separate iterations were made to the implant plan. The final version of the implant plan was included as part of a comprehensive operations plan for the SEACON II structure [4-1]. In addition to the step-by-step procedures for installing the structure, the plan contained detailed information on site properties, navigation systems, schedule, personnel responsibilities, contingency plans, communications plan, and hazard analysis.

##### EQUIPMENT

The CFI, Warming Tug (Figure 4-1) was selected as the installation vessel. The tug, fabricated from 4 x 4 x 7-foot pontoons, is 120 feet long with a 35-foot beam. The tug's 2-foot freeboard and no gunnel facilitate moving equipment from deck to water and back, but limit it to operating in a maximum sea-state-3 condition. Twin



Figure 4-1. CFI's warping tug SEACON II implant vessel.

300-horsepower diesel engines drive hydraulically controlled tail sections for propulsion (maximum 5 knots) and maneuvering. Wheel house, winch house, and living quarters are located within the after superstructure. The forward open deck (1,700 square feet) provides adequate space for rigging operations and installation equipment. The bow A-frame and the main three-drum winch (located in the winch house) are designed for handling up to 70,000-pound loads. A 15-ton deck-mounted crane, which is used for on-deck and over-the-side load handling, is located on the forward deck. The tug is equipped with lifesaving equipment, navigational gear, and quarters for cruise personnel.

A diesel/hydraulic traction winch (20,000 pounds line pull at 200 fpm) was selected to handle most of the structural cables. The winch was mounted on the port side of the tug's open deck with a 42-inch-diameter deck sheave mounted under the A frame.

Three types of navigation systems were employed during implant operations. LORAC B and radar were

used during transit, and, once on site, the primary navigation system was the acoustic transponder navigation system (ATNAV). LORAC B, which was discussed in Chapter 2, is a locally maintained and operated surface radio navigation system capable of providing position accuracies of about  $\pm 50$  feet at the SEACON II site. Radar, in addition to navigation, established the position of the implant vessel with respect to various surface buoys. The ATNAV system provided a real-time continuous x-y plot and x-y-z print-out of the positions of the surface ship and a midwater transponder on the item being installed relative to three bottom-moored and surveyed transponders.

CFI's LCM-8 boat was selected to provide diver support and personnel transportation functions as well as to implant and survey the ATNAV system. This 74 foot-long modified landing craft cruises at 14 knots and is equipped with radar, AM and FM radios, a LORAC B navigation receiver, a small A-frame forward, and a 1-ton hydraulic cherry picker amidship.

Prior to commencement of installation operations, all critical equipment was tested to insure it met implant requirements.

## PROCEDURES

The implant of the SEACON II structure was divided into eight separate phases, each of which was designed to be accomplished in one day or less. Figures 4-2 and 4-3 show the installation sequence.

During Phase I of the operations the LCM-8 boat free-falls the three bottom-moored acoustic transponder navigation system (ATNAV) transponders and surveys them in. LORAC navigation determines ship position and is the tie between geographic coordinates and the transponder net location.

Phase II involves the warping tug installing a single-point moor at the site to be used in the remaining phases. The moor is implanted with an explosive embedment anchor lowered from the warping tug and fired on impact. A 9-1/2-foot-diameter by 5-foot-high foamed mooring buoy (MB) is attached to the mooring line.

During Phase III legs L1 and L2 are installed. A midwater transponder attached 50 feet above the anchor positions the explosive embedment anchors A1 and A2 in the ATNAV coordinate system. The procedure is as follows:

1. Lower anchor to within 150 feet of bottom.
2. Maneuver ship to final position with ATNAV.
3. Lower anchor to seafloor (which triggers the explosive charge).
4. Load test anchor.
5. Recover midwater transponder.
6. Pay out line.
7. Attach and deploy temporary buoy (SB1).

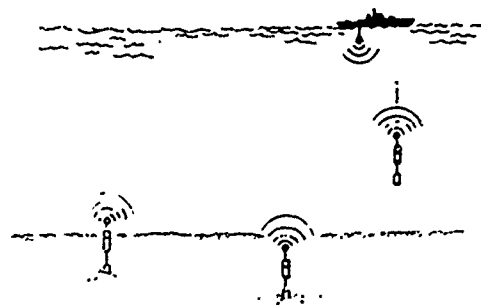
Lowering is accomplished with the traction winch, and buoys are deployed with the crane. During the deployment of A2 and L2, a tag wire is attached to the buoy on L1 to keep L1 taut and to prevent hocking. When A2 and L2 are deployed, the remaining end of the tag wire is attached to the temporary buoy on L2, thus restraining the movement of L1 and L2.

Phase IV involves removing the temporary buoys on L1 and L2 and installing the three node buoys (NB1, NB2, and NB3), two EM delta arms, and L3. The three node buoys are connected to the delta arms at dockside, and the cables are figure-eighted on deck. This procedure minimizes the number of at-sea electrical connections. The temporary buoy at L2 is recovered and replaced with NB2. The tag wire to the other temporary buoy is slacked to relax the moor. A second tag line (buoyant line) is attached to NB2; this line is payed out with a winch. Temporary floats are attached to the delta cable and the buoyant tag line every 150 feet to reduce the deployment load so that the EM delta cable can be payed out by hand. At L1 the temporary buoy is removed and replaced with NB1.

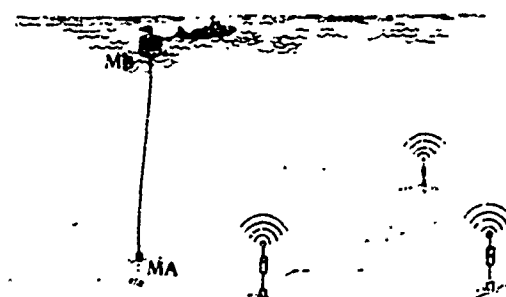
After all three node buoys are deployed, NB3 is recovered with the crane. With the buoy secured to the deck, the electrical and mechanical connections of L3 are made. L3 is payed out with the traction winch while the vessel moves in the direction of the construction mooring buoy (MB). The position of the ship relative to the amount of L3 payed out is carefully maintained according to precalculated distances and tensions. Electrical and electronic tests are performed when L3 is payed out. A synthetic line is attached to the end of L3. The tug moves to the mooring buoy while paying out this synthetic line. At the mooring buoy, the synthetic line is hauled in until the node buoys submerge. A spar buoy attached to NB3 is used to determine when the buoys are submerged. When the node buoys are submerged, the synthetic line is attached to the mooring buoy.

Phase V, which is the installation of the final delta arm, is accomplished similarly to the delta installation by using tag wires on both the buoys and temporary floats to relieve the strain on the cable handlers. The delta is again submerged following this installation.

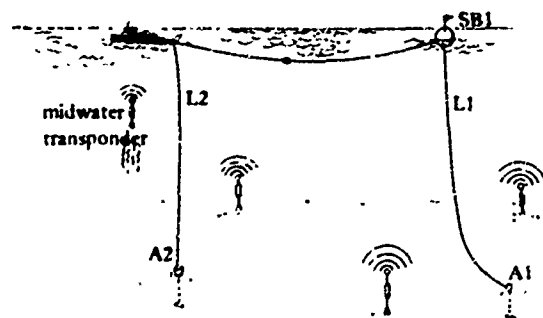
Phase VI is the most complex part of the installation due to the heavy weights, multiple lines, and precise positioning involved. The node buoys are surfaced by slackening the synthetic line between MB and the end of L3. A wire attached to MB is payed out over the stern of the vessel, while the synthetic line is recovered over the bow. In this manner the end of L3 is recovered. The stern line to MB is used later to help maintain station during the clump anchor (A3) positioning. With the end of L3 on deck,



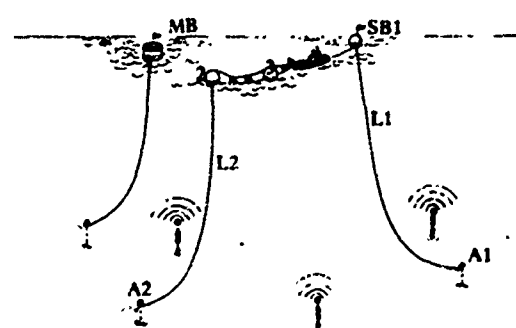
(a) Phase I - transponder installation and survey.



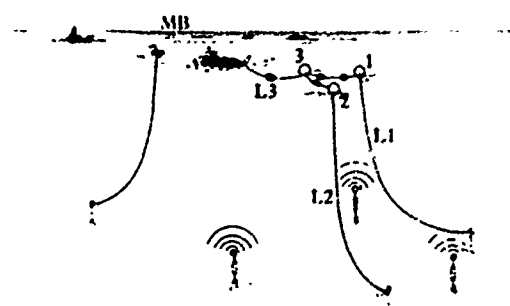
(b) Phase II - construction moor implant.



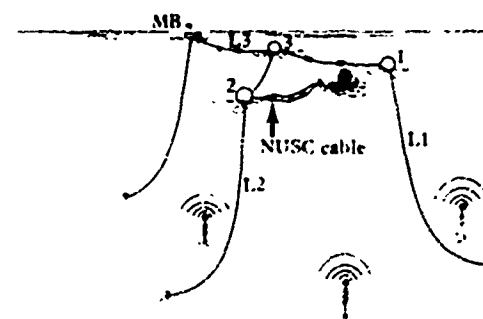
(c) Phase III - mooring leg L1 and L2 implant.



(d) Phase IV - EM delta installation.

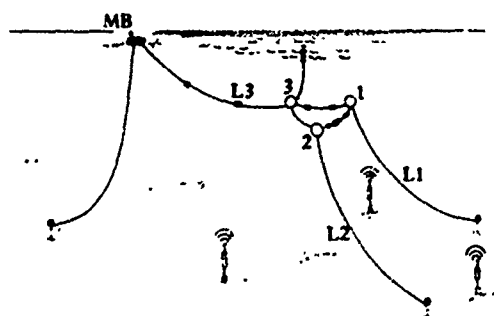


(e) Phase IV - pay out of L3

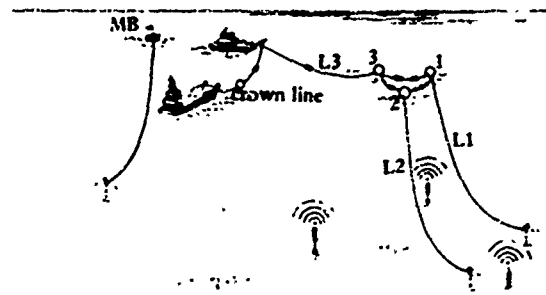


(f) Phase V - installation of NUSC cable in delta section.

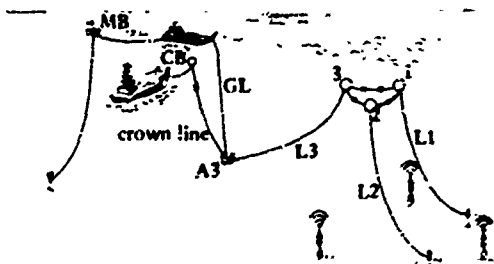
Figure 4-2. SLACON II installation sequence - Phases I through V



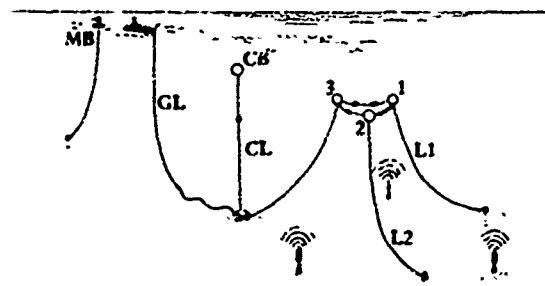
(a) Phase V - completed delta in protective moor.



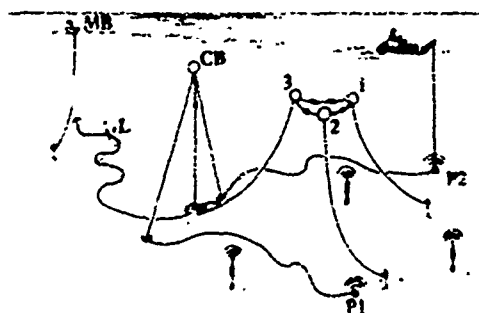
(b) Phase VI - payout of crown line.



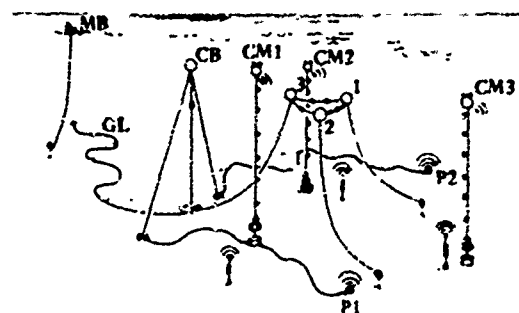
(c) Phase VI - clump anchor deployment.



(d) Phase VI - installation of grapnel line.



(e) Phase VII - projector implant.



(f) Phase VIII - current meters implant.

Figure 4-3. SFACON II installation sequence - Phases V through VIII.

electrical tests are performed, and the cable is attached to A3. A second boat, the LCM-8, pulls the crown buoy (CB) away from the tug as the crown line is deployed. The end of the crown line is then attached to the clump anchor, and final electrical and electronic tests are performed.

The clump anchor is lifted off the deck with the ship's winch and bow A frame. The load is then transferred to the grapnel wire on the traction winch. Before lowering, a midwater transponder is attached to A3. As A3 is lowered, the tug moves to position using the ATNAV system. The positions of the second boat and the CB are monitored with radar. With A3 in position, the grapnel (lowering line) is payed out and deployed.

Phase VII involves the installation of two projectors. Divers are used to recover a projector cable pigtail from the crown buoy, which is 50 feet deep. Following attachment to the projector cable, the pigtail is reattached and strain-relieved to the crown buoy by divers. The ship is positioned over the implant site using ATNAV. The projector wire is payed out with a small winch. The projector is lowered to the bottom, and a release device is used to recover the lowering wire. The second projector is installed similarly.

During Phase VIII, three current meter strings are installed by controlled lowering (anchor first). The strings consist of buoyancy at the top and bottom (redundant), as well as two release devices located just above the clump anchors. Phase VIII completes the installation process.

## TRAINING

All implant personnel were thoroughly instructed in each phase of the operation. This instruction included an at-sea training cruise in addition to briefings held aboard ship before every critical step during the actual implant operation.

The at-sea training on critical phases of the installation was conducted aboard the Warming Tug with actual or well-modeled structure components. This cruise not only supplied an opportunity to instruct personnel but also test the installation techniques and equipment.

The training cruise was scheduled just 2 weeks prior to the actual implant so the experience would

not be dimmed by a long time lapse. The operation was conducted in 300 feet of water which made ship positioning more critical than in the actual implant in 2,900 feet of water. Figure 4-4 shows training for the most critical phase of the implant - the crown buoy/crown line/clump anchor deployment. During this phase the actual 8-ton clump was implanted, but without the power and instrumentation equipment installed.

The operation was scheduled for a 4-day period so that significant problems and delays could be handled. However, the training proceeded so smoothly it was completed in 2 days. Numerous minor changes were made to equipment and procedures as the result of the exercise, but no major modifications were found necessary. Using the ATNAV system as a guide for ship positioning was found to be very convenient and workable even in such a shallow water depth.

## SECTION 2 - SEA OPERATION

### PHASE I: ATNAV TRANSPONDER INSTALLATION AND SURVEY

Phase I, the implant and survey of the acoustic transponder navigation system (ATNAV), began on 30 July 1974 aboard the LCM-8 boat (Figure 4-5). It was expected the operation would be completed in 1 day as noted in Table 4-1. However, a weld parted on a buoy package causing the second of the three transponders to fall to the bottom unbuoyed. The transponder still operated, even though it lay on its side and was about 3,000 feet from its planned implant position. The first transponder installed would not turn off (disable) on command, nor would it release. The installation of the third transponder and the survey part of Phase I were delayed 1 day in order to assess the situation. It was determined that the location of the unbuoyed transponder, although not ideal, was satisfactory, and that there was no critical need to be able to disable the one transponder. So on 1 August 1974, the third transponder was installed, and the three transponders were successfully surveyed. The survey data were analyzed, and ATNAV coordinates were determined for the desired embedment anchor locations.

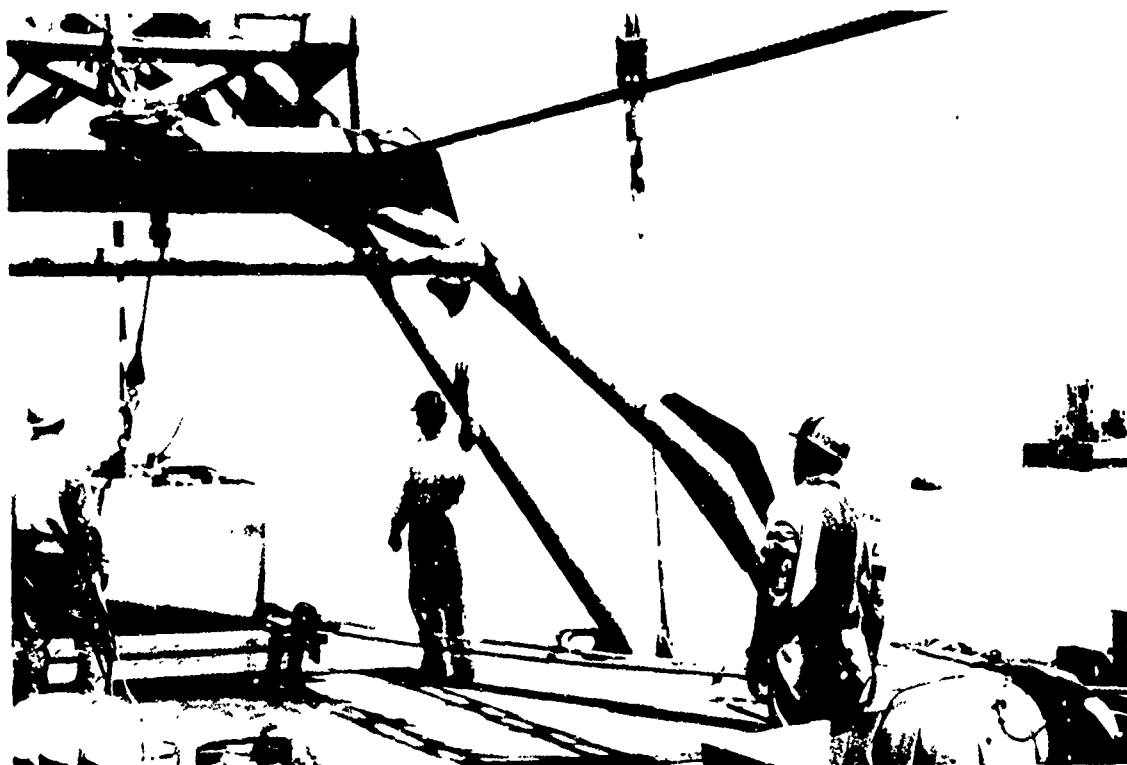


Figure 4-4. Training for crown line, crown buoy, and clump anchor deployment with CEL warping tug and LCM-8 boat.

#### PHASE II: CONSTRUCTION MOOR IMPLANT

On 5 August 1974, the Warping Tug was on site at first light. The ATNAV system was activated and checked against LORAC; they did not agree. The discrepancy appeared to be one green lane on LORAC, which is equivalent to about 600 feet. However, it could not easily be determined if the error was in LORAC or if ATNAV was giving erroneous positions because the ship was outside the triangle formed by the three bottom transponders. It was decided to assume the problem was with ATNAV, and, thereby, to implant the mooring anchor using the LORAC navigation system. If this turned out not to be the case, there would be a 600-foot error in the construction moor position, but it would present no serious problems.

The explosive embedment anchor, Figure 4-6, was installed in a very routine manner. Tension in excess of 15,000 pounds was applied to set the anchor fluke

and to proof-test its embedment. Then, the remainder of the mooring line was paid out, and the mooring buoy was attached and cast off (Figure 4-7). Phase II was completed in about 2 hours, 2 hours less than estimated in the operation plan [4-1].

#### PHASE III: MOORING LEG 1 AND 2 IMPLANT

After a weather check indicated favorable weather was expected for at least another 4 hours, it was decided to proceed with Phase III.

The Warping Tug was put on a course over the top of one of the ATNAV transponders in order to determine the cause of the navigation discrepancy. While directly over the transponder, the one green lane discrepancy in LORAC still existed. This indicated ATNAV was giving consistent readings and that the LORAC was either one green lane in error during this cruise or during the ATNAV survey cruise



Figure 4-5. ATNAV bottom transponder being deployed from LCM-8 boat.

Since the closest LORAC calibration point was at Port Hueneme Harbor and the possible 600-foot shift to the northeast in locating the structure did not pose significant problems, it was decided to proceed with the implant using ATNAV for positioning. The exact geographic position of the structure would then be determined during a later cruise.

The ATNAV X-Y plotter was located on the bridge so both the pilot and navigator could see it. The anchor was lowered to within 150 feet of the bottom initially and then to within 60 feet as the site was neared so that the anchor could be quickly installed once the ATNAV system indicated it was within the target area. Figure 4-8 shows the ATNAV position data for the ship and the transponder on the anchor as the ship attempted to maneuver the anchor

to the desired location. When it appeared that the anchor would pass about 60 feet north of the target, the ship's heading was reversed. It was hoped this would also reverse the path of the anchor. When point 11 (Figure 4-8) for the anchor plotted, it appeared that the reversal had occurred, and the order was given to lower the anchor to the bottom. The next three ATNAV interrogations resulted in no anchor position data. The fourth reading taken about 3 minutes after implant indicated the anchor was about 120 feet northeast of the target position. The data points that followed clustered around that reading, indicating point 11 was a spurious one. Based on Figure 4-8, the scatter in the data for the implanted anchor position appears to be about  $\pm 5$  feet in the y-direction (north and south) and  $\pm 15$  feet in the x-direction (east and west).

The offset between the actual location and target position of A1 was used to shift the target coordinates for anchor A2, since only well-controlled relative anchor positions were important to a satisfactory implant. The A1 anchor implant acted as a training exercise on "flying" in an anchor to a target position. The experience gained on this installation was applied to the implant of the other two anchors in which position accuracy was critical.

Depth data were also monitored during implant to determine the depth the anchor had keyed into the seafloor after it had been set and proof-tested with a 10,000-pound vertical load. Figure 4-9 shows schematically how the fluke embedment depth was determined. This indirect method of calculating depth was unsatisfactory. A small error percentagewise in water depth or ATNAV readings results in a significant error in calculating anchor fluke embedment depth.

After the structure was recovered, corrosion products were found on the anchor cable attached to the fluke which indicated it had been embedded in the seafloor approximately 20 feet, 4 feet deeper than calculated.

The transponder on the anchor line was successfully released, and it followed the line to the surface in about 8 minutes. The remainder of leg L1 was paid out, and the end was connected to a temporary mooring buoy, as shown in Figure 4-10. This completed the leg implant and testing, which took about 3 hours.





Figure 4-6. Deep water explosive embedment anchor being deployed from bow of warping tug.

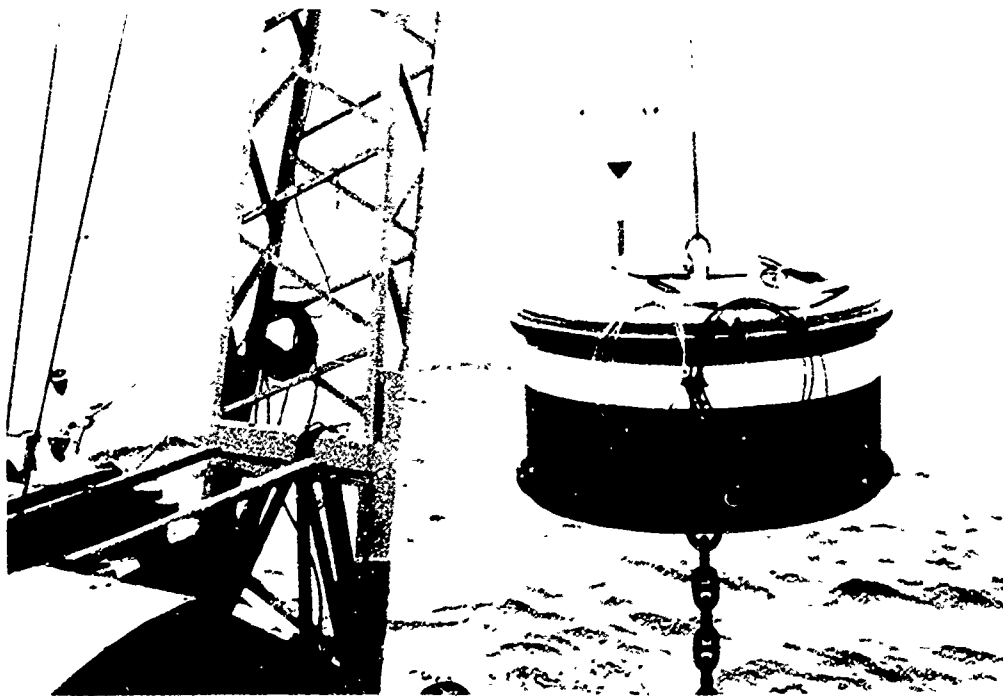


Figure 4-7. Construction mooring buoy being deployed.

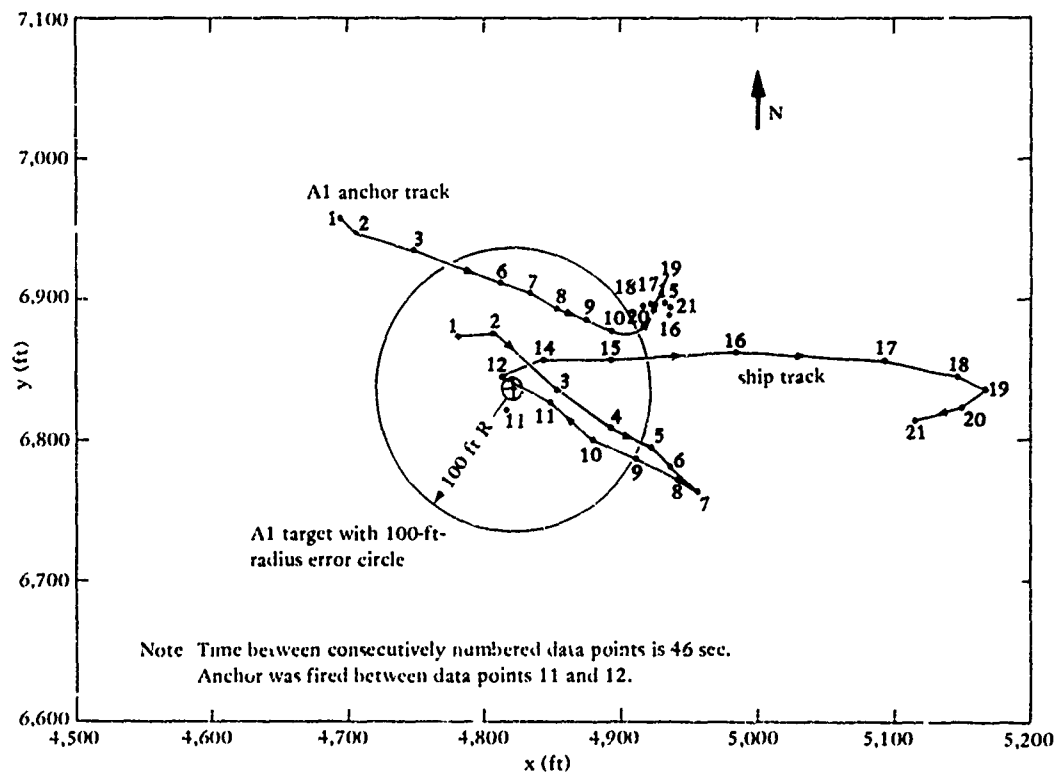


Figure 4-8. ATNAV position data for ship and anchor A1 during implant.

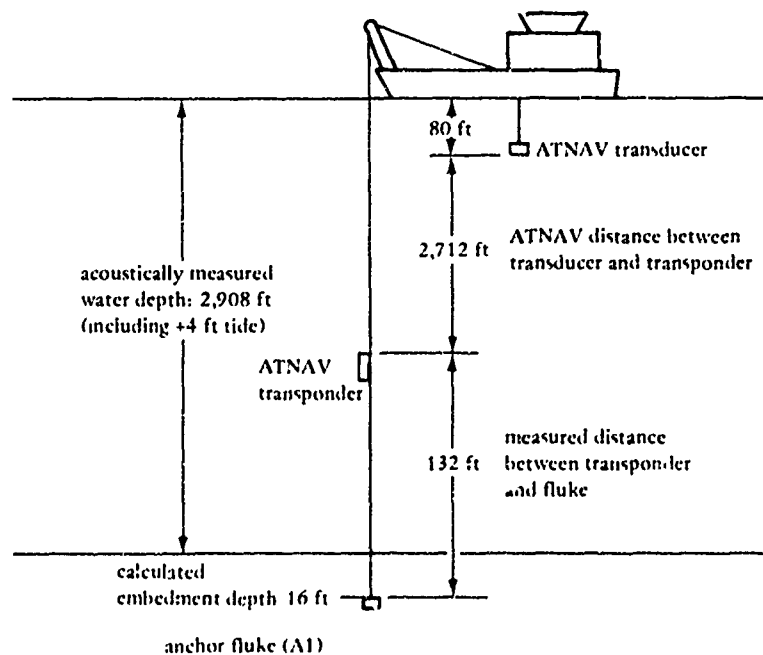


Figure 4-9. Determination of anchor embedment depth using measured water depth and ATNAV readings.

Table 4-1. Projected and Actual Implant Schedule

Phase No.	Staging and Loading		Cruises			Remarks
	Planned (days)	Actual (days)	Planned (days)	Actual		
				Days	Dates	
I	2	2	1	2	30 Jul and 1 Aug 74	Buoy failure caused survey delay.
II and III	1	1	1 + 1 <sup>a</sup>	1	5 Aug 74	Preparation and cruise days matched schedule.
IV and V	1	6	1 + 1 <sup>a</sup>	3	12, 13, and 16 Aug 74	Extra cruise day due to removal and repair of node electronics.
VI	2	8	1 + 1 <sup>a</sup>	1	29 Aug 74	Cruise day matched schedule.
VII and VIII	1	6	2	2	11 and 12 Sep 74	Cruise days matched schedule.
Total	7	23	6 + 3 <sup>a</sup>	9		Actual cruise days equaled total planned, including contingency days. Staging and loading tripled expected time.

<sup>a</sup>Contingency day.

Anchor A2 was installed in a manner similar to A1, but it was complicated by three factors. First, the winds and, consequently, the seas began to increase after A1 was installed, making it more difficult to handle equipment over the side and to maneuver the tug. By the end of the operation an upper sea state 3 existed. Second, tug maneuverability was further restricted by having a tag line from the tug to leg 1.1. Finally, the ATNAV system began malfunctioning, thereby causing a loss of two-thirds of all anchor and one-third of all ship position data points. Figure 4-11 shows the track lines for the ship and anchor. When point 5 plotted, it appeared the anchor would pass north of the target, so the ship heading was changed. No anchor positions were obtained for over 4 minutes, then point 10 plotted on the same course indicated by points 1 and 5. Another course change

was made to the southwest to try to pull the anchor south and slow down its easterly movement. After one skip, point 12 plotted which showed the anchor had passed the site. The tug was then put on a westerly course to try to pull the anchor back to the target. However, 6 minutes passed before another good position plotted. Then, after one skip, five good points plotted, ending with point 25 just 35 feet east of the target. The tug continued to move slowly east, and, when anchor positions for points 26 and 27 were missed, the decision was made to implant based on extrapolating anchor positions 23 through 25.

The first plot after the anchor fired was point 28, which appears to be spurious datum. Then points 32 through 41 were obtained, which show the implanted position to be some 70 feet southeast of the target, relative to water depth this is an implant accuracy of

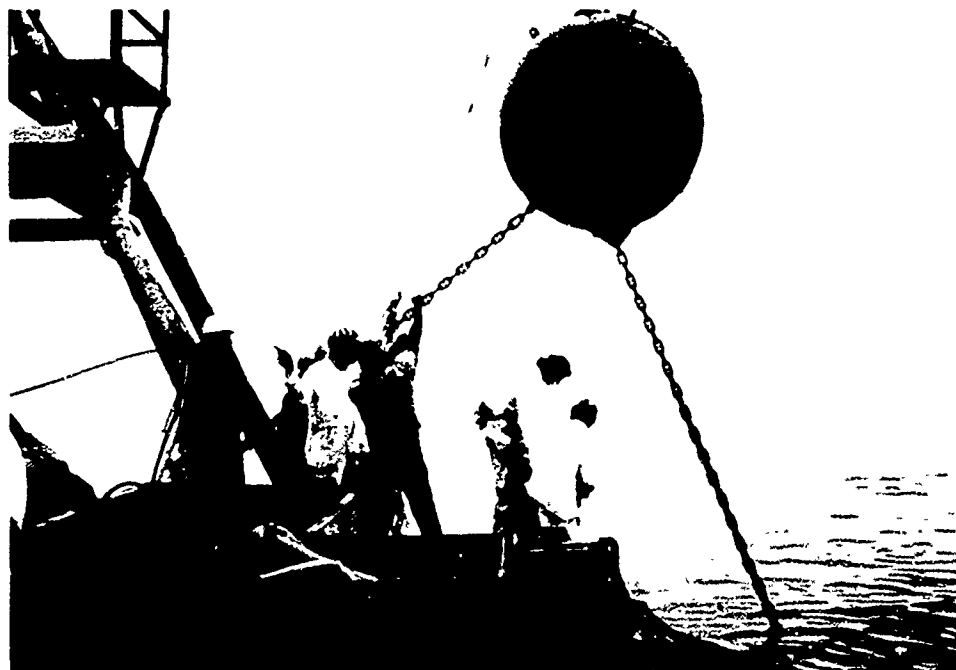


Figure 4-10. Deployment of one of the two temporary mooring buoys that support legs L.1 and L.2 during Phase III.

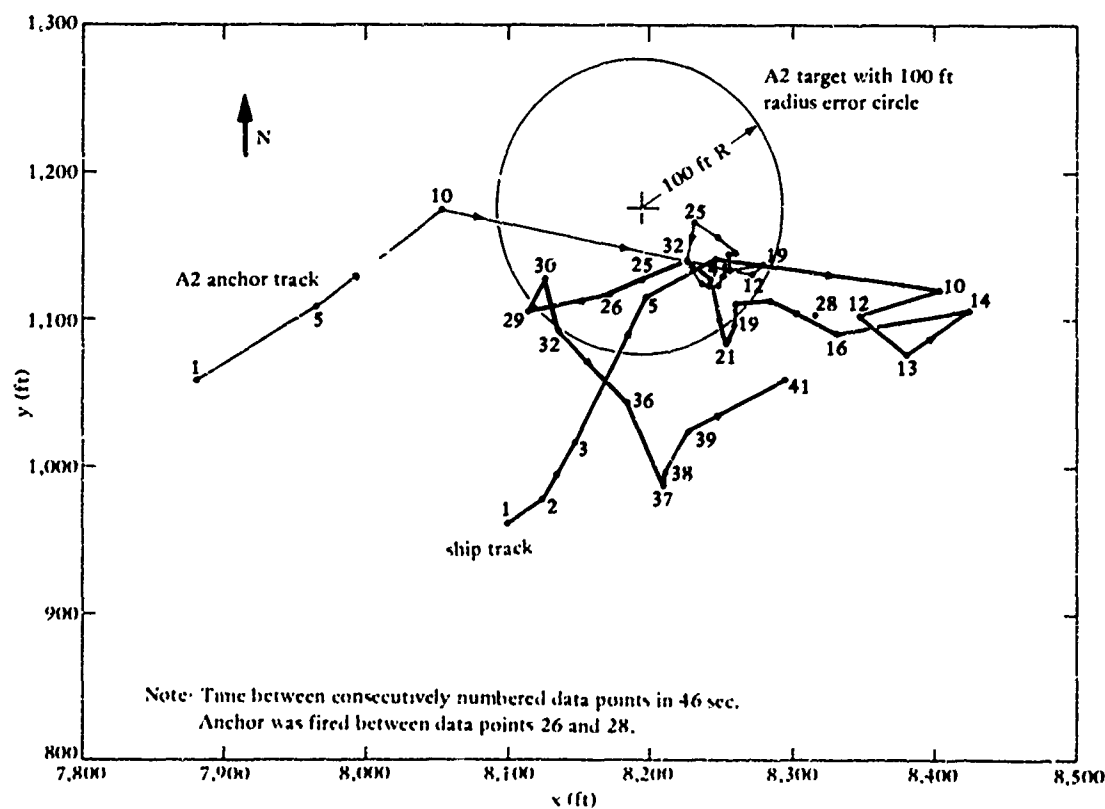


Figure 4-11. ATNAV position data for ship and anchor A2 during implant.

about 2%. The scatter in the A2 anchor position data appears very similar to that for A1, about  $\pm 5$  feet in the y-direction and  $\pm 15$  feet in the x-direction.

Analysis of the ATNAV position data indicates the distance between anchors A1 and A2 was 6,658 feet, which is 62 feet or 0.94% more than the target of 6,596 feet.

The distance between the ATNAV transducer and ATNAV transponder on the anchor line was monitored once again to determine anchor penetration depth. Analysis of the data, using the same technique as shown in Figure 4-9 for anchor A1, resulted in a calculated penetration depth of 73 feet for the A2 fluke. This contrasts with visual data obtained with the *CURV III* submersible, which indicate the fluke was embedded only about 8 feet. In any case, the anchor was successfully loaded to about 10,000 pounds to set the fluke and insure it would develop sufficient holding capacity to anchor the SEACON II structure.

Once anchor positioning was completed, the submersible transponder was successfully released and recovered. The remainder of leg L2 was paid out, buoyed off, and connected to the tag line running to the temporary mooring buoy on leg L1 (Figure 4-2c). The deployment and testing of anchor A2 and leg L2 required approximately 3-1/2 hours. Phase III from beginning to end required 11 hours, 4 hours more than estimated in the operations plan [4-1].

#### PHASE IV: INSTALLATION OF DELTA

After 1 week in port to complete final assembly and environmental testing of the delta section and loading operations, the warping tug put to sea again on 12 August 1974, arriving on site at first light. The seas were nearly dead calm—only a 1-foot swell and no wind chop. The forecast was for 6-to-10-knot winds and 2-to-3-foot seas in the afternoon, well within bounds for the operation.

Figure 4-12 shows the three node buoys and two delta arms figure-eighted in boxes on deck. The implant was made from the starboard side of the tug, beginning with node buoy NB2 as depicted in Figure 4-2d.

The first of the 1,000-foot arms, temporarily buoyed with pillow floats, was deployed, followed by

the middle node buoy, NB3 (Figure 4-13). As each of the instrument stations preassembled on the arm cables was reached, it was carefully placed into the water with the crane (Figure 4-14).

After the entire delta assembly was in the water, the middle node buoy (NB3) was recovered and held over the starboard bow. The end of leg L3 was terminated electrically and mechanically to the buoy, and then paid out. The ATNAV system was used to position the tug during this entire phase. Position control was especially important during payout of leg L3 to insure the maximum allowed tension of 2,000 pounds in the leg was not exceeded. Load-displacement predictions were used to determine desired tug position as leg L3 was paid out. The ATNAV system reliably provided tug position, no submersible transponder positioning was involved in this phase.

Once the end of leg L3 was reached, electrical checks were made on the implanted equipment. All the electrical conductors had continuity, none were shorted to each other or to seawater. An attempt was made with an oscillator to manually turn on each of the hydrophone canisters, two of the seven would not respond. One of these was in NB1, the other on the arm between NB2 and NB3. Since failure of the hydrophone canisters was unacceptable, the contingency plan [4-1], which called for recovery and repair of the canisters, had to be implemented. But first, due to the late hour, the tag line connecting the end of leg L3 to the construction mooring buoy (MB), as shown in Figure 4-2d, was paid out, and the structure was pulled underwater overnight. The tug moored on site.

Approximately 13 hours was required to complete Phase IV instead of the estimated 8 hours.

The weather on the morning of 13 August 1974 was excellent with good forecasts for the entire day, so the canister recovery operation was initiated. With NB1 above the starboard bow, the electrical system was checked again. All was perfect after soak-testing night except for the two canisters that would not respond. Finally, the NB1 canister was activated, but at a much higher than designed voltage, since this was unacceptable, it was removed for repair at CFL.

The canister at the middle of the arm between NB2 and NB3 was more difficult to reach since it was submerged about 100 feet. Divers placed a buoyed

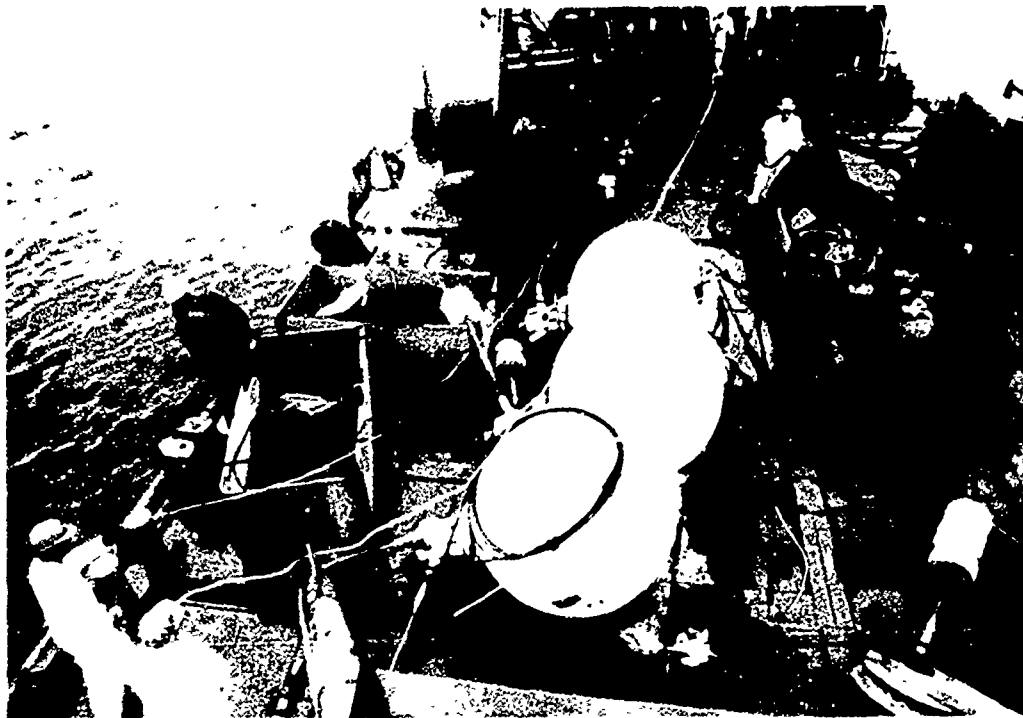


Figure 4-12. Node buoys and figure-eighted delta arms ready for deployment during Phase IV.

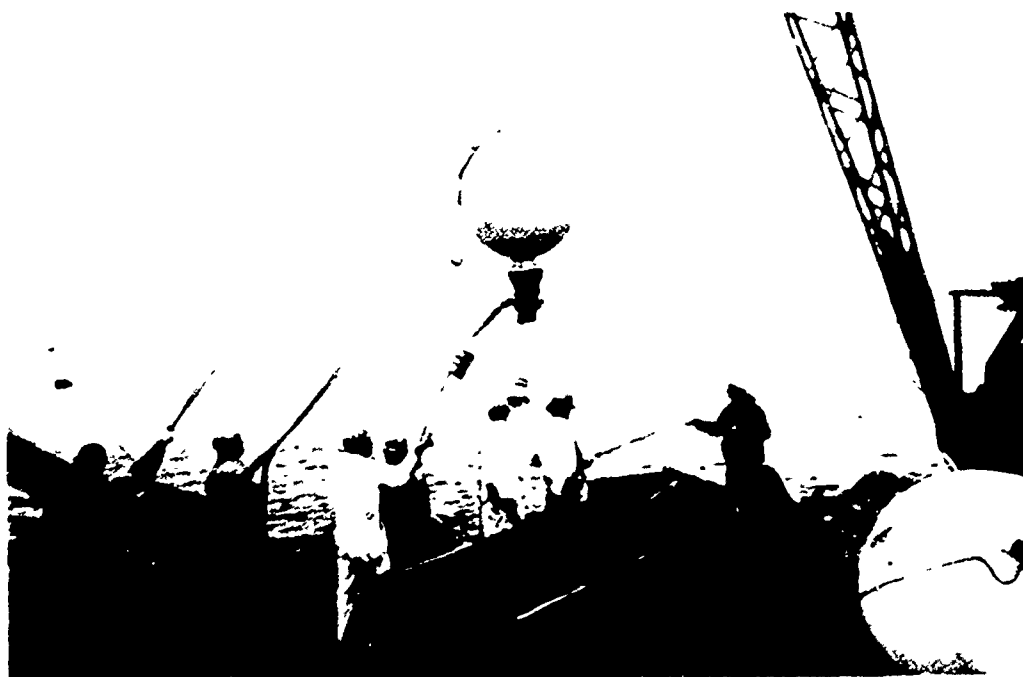


Figure 4-13. Middle buoy (NB3) on delta arm being deployed. Delta arm buoyed with pillow floats.

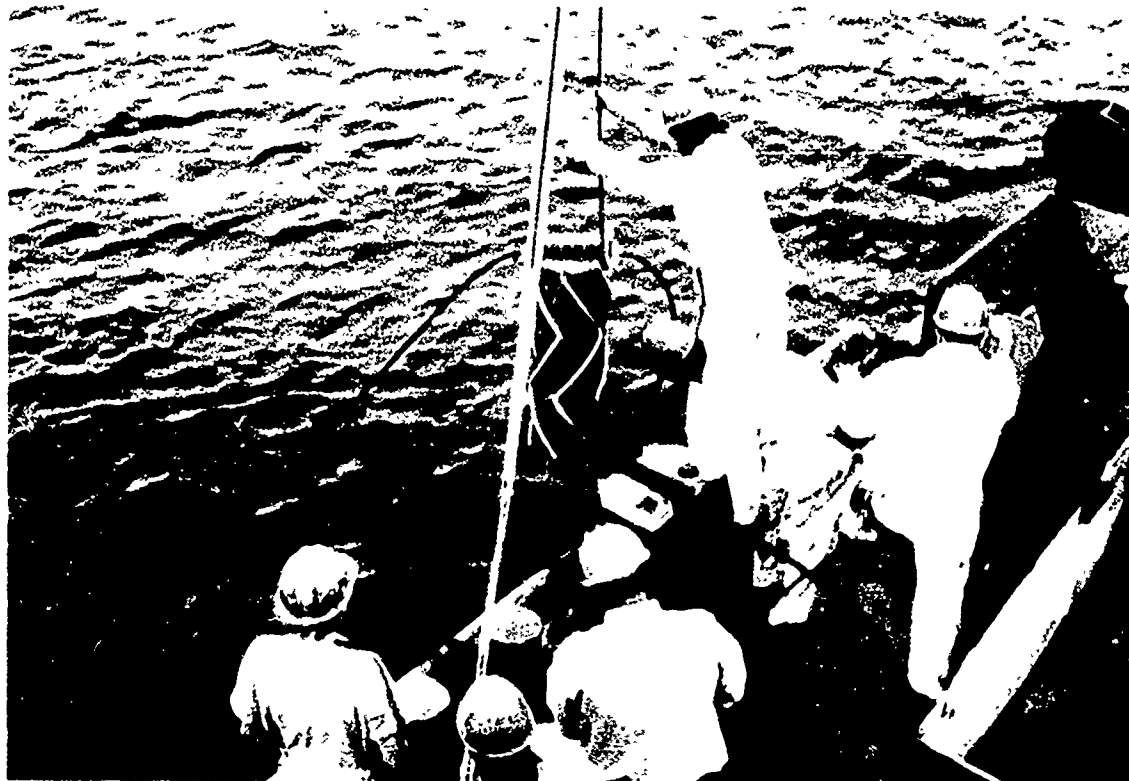


Figure 4-14. Instrument station on delta arm being deployed.

sheave on the arm near NB3 and passed a tag line to the warping tug. Using AFINAV for position control, the tug pulled the sheave along like a trolley until it reached the canister. The canister was then pulled to the surface, and the arm was stopped off to the tug on each side of it. The canister was then removed and replaced with a weight to simulate the canister. The stoppers were cut, and the arm was allowed to drop down in a catenary. The moor was resubmerged by hauling in on the tag line from leg L3 and attaching it to the construction mooring buoy. This recovery procedure required approximately 8 hours, after which time the warping tug returned to Port Hueneme.

#### PHASE V: NUSC DELTA ARM INSTALLATION

Two days were required to repair NB1's hydrophone electronics. The midline canister could not be repaired; it had flooded with seawater. The warping

tug headed for the site again on 16 August 1974 to reinstall NB1's hydrophone canister and to install the third arm of the delta, which had been provided by NUSC, New London.

The tag line to the construction mooring buoy was slackened to surface the delta. The midpoint on the arm between NB2 and NB3 was surfaced by the trolley technique described earlier. The weight simulating the canister was removed, and the electrical conductors were resealed using the cable splicing techniques described in Chapter 3 to insure against leaks. After the work on the arm was completed, it was resubmerged. Then, NB1 was recovered, and the canister was reinstalled in it. Electrical checks showed continuity existed throughout the structure, and all canisters turned on.

The repair operation was completed by 1230, and installation of the NUSC arm was initiated. A tag line was attached from the warping tug to an 80 foot mechanical cable pigtail with an electrical cable and connector married to it at NB1. The tug then moved

over to NB2 while paying out this tag line. At NB2 the NUSC arm was connected mechanically to its 80-foot pigtail. The NUSC arm was then paid out in the same manner as the other delta arms while the tag line to NB1 was hauled in (see Figure 4-2f). After arriving at NB1 the electrical connector was plugged together, a mechanical connection was made, and then the stoppers to each side of the connection point were cut, releasing the arm.

To resubmerge the structure in a protective moor as shown in Figure 4-3a, the line from the end of leg L3 to the mooring buoy was hauled in. When the structure was properly submerged, the static tension at the mooring buoy was about 2,000 pounds compared to the predicted 1,783 pounds. The somewhat higher tension is probably due mainly to the construction moor being about 600 feet farther away from the SEACON II structure than was assumed for the prediction.

Phase V, excluding the repair work, was completed in about 4 hours time, which is 1 hour less than estimated in the operation plan [4-1].

#### **PHASE VI: INSTALLATION OF CLUMP ANCHOR AND ASSOCIATED CABLES AND BUOYANCY**

After spending 1-1/2 weeks in port outfitting the crown buoy and clump anchor, the warping tug was loaded and put to sea on 29 August 1974 to conduct Phase VI of the SEACON II implant. Arriving onsite at first light, the line from the structure to the mooring buoy was first slackened to resurface the node buoys. A mooring line from the stern of the warping tug was then paid out, while the line to the end of leg L3 was hauled in over the bow. Once the end of L3 was recovered, the electronics seaward from the end of L3 were checked again and found to be operating well except for one tension cell. Meanwhile, the LCM-8 boat and CEL divers proceeded to each node buoy as it surfaced to add and subtract weights and buoyancy material according to a revised schedule determined by the DESADE computer program.

While arc welding two protective pipes for the acoustic projector electromechanical pigtail cables on the crown buoy (see Figure 4-15), a steel strength

member on one projector pigtail was damaged. The mechanical strength of the member was not compromised; however, it was feared that damage might have been done to the electrical conductors. Indeed, a continuity check revealed only a 1,200-ohm resistance from the common conductor to ground. Since the signal and plus power conductor appeared okay after studying the wiring diagrams, it was decided that no serious problem existed and implant should not be delayed. The seas were good and the forecast was excellent, so the decision was made to proceed with the implant.

For the first time during the implant, close coordination was required between two vessels. The LCM-8 boat took the crown buoy in tow as the crown line was paid out (Figures 4-3b and 4-16). The LCM-8 boat had a tension cell on board to monitor horizontal load. A plot of distance between the warping tug and LCM-8 boat versus horizontal load was used to determine the desired position of the LCM-8 boat relative to the warping tug to insure the crown line was neither too slack or taut. The warping tug radar provided a digital read-out of distance to the LCM-8 boat which made control in this fashion very convenient. However, when approximately one-half of the crown line had been paid out, the load cell quit operating. Therefore, it was necessary to switch to a backup method. A plot was used in which ideal distance between the two vessels (equal to 70% of the length of crown line paid out) was plotted versus length of crown line out. This method was very convenient to use since the crown line was marked every 100 feet and the warping tug radar provided distance data to the LCM-8 boat.

After the end of the crown line was reached, it was connected electrically (seven wires) and mechanically to the clump anchor. This required approximately 1 hour while the LCM-8 boat held the crown buoy off the starboard bow. The clump was then placed overboard (Figure 4-17) with a midwater transponder tethered 12 feet above it and then lowered to the bottom on a 1-1/8-inch wire rope from the traction winch. The lowering and maneuvering operation (Figure 4-3c) required approximately 1 hour. The clump was held about 50 feet off the bottom until it was within about 30 feet horizontally of the desired location, then it was lowered to the bottom. However, once on the



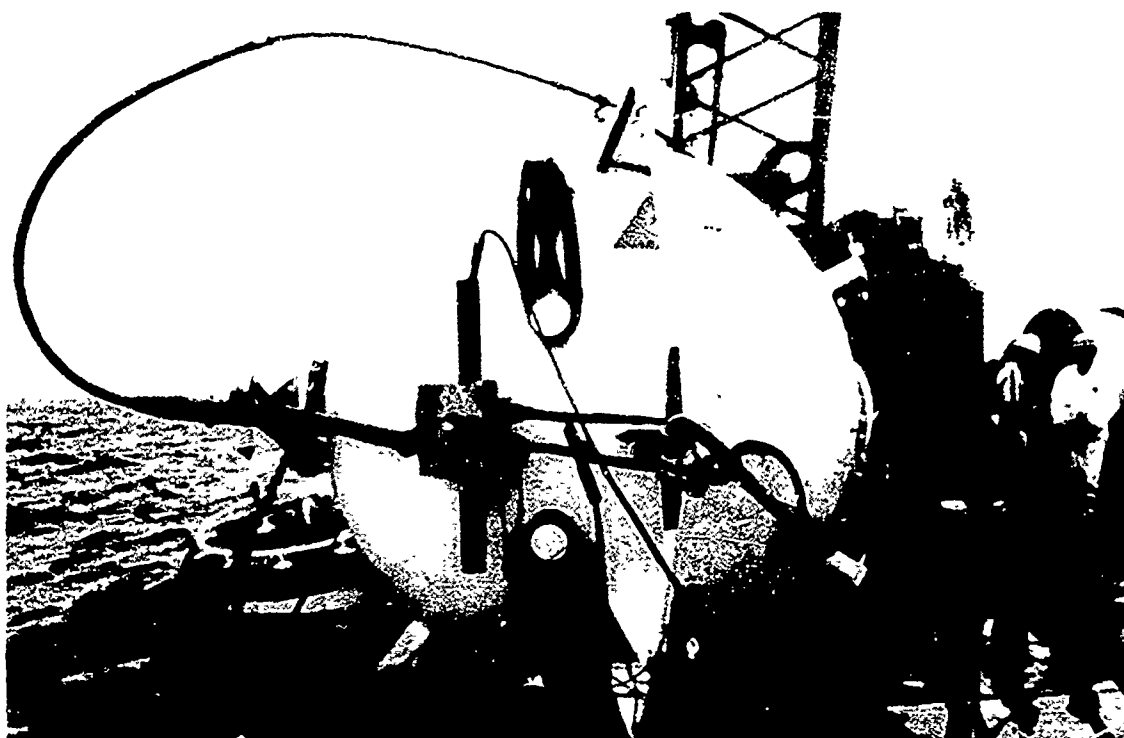


Figure 4-15. Crown buoy aboard warping tug. Crown line terminated on left side of photo (bottom of buoy). Two projector pigtails figure-eighted on bitts and running to junction box with protective pipes top and bottom.

bottom, erroneous response times were received from the unbuoyed transponder because the direct path between the midwater and unbuoyed bottom transponders was being shadowed. The result was inaccurate clump position data. Since it was critical that the precise final location of the anchor be determined, it was decided to resurface the anchor and lengthen the tether line on the midwater transponder to 70 feet, which would place it high enough off the bottom to obtain accurate position data. An additional 150 pounds of buoyancy was added to the midwater transponder tether to combat the effect of drag on the longer tether line. Figure 4-18 shows the maneuvering operation which required about 15 minutes to complete. Due to the horizontal component of tension from leg 1.3, the clump was pulled as expected about 600 feet out in front of the warping tug. Nevertheless, the clump was placed within 15 feet of the target location. The stern line to the construction mooring buoy aided considerably in controlling the warping tug position and, in turn, the

clump position. The ATNAV system worked very reliably once the submersible transponder was tethered 70 feet off the bottom. This facilitated the positioning of the clump anchor immeasurably over the situation encountered during the implant of anchor A1 and A2.

The effect of the ship velocity on accuracy of the acoustic positioning system can be seen by comparing anchor position data points with corresponding ship positions in Figure 4-18. The warping tug movement at only 1 fps to the northeast appears to bias the calculated anchor position about 10 to 20 feet to the northeast. When the ship heading changed, the direction in the anchor position bias changed as well.

After obtaining sufficient position data on the clump anchor, the submersible transponder was acoustically released and recovered. The 3,500-foot-long grapnel line used to lower the clump was paid out (Figure 4-3d), and a tag line connected it to the construction mooring buoy to simplify recovery should that be necessary.



Figure 4-16. Crown buoy taken in tow by LCM-8 boat off warping tug starboard bow.

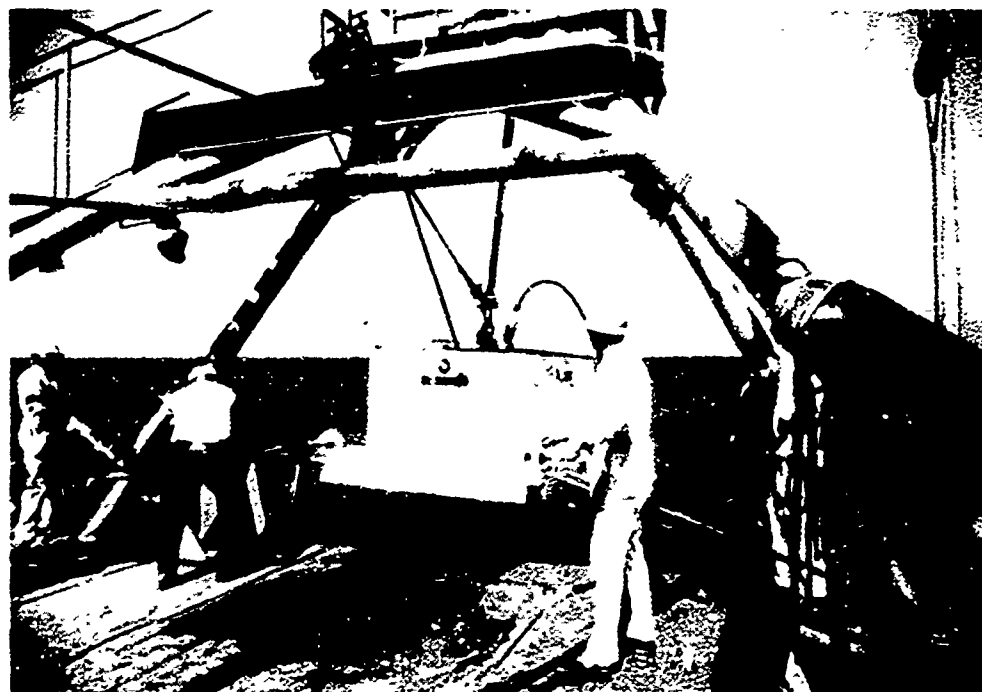


Figure 4-17. Light-ton clump anchor containing RPC being placed overboard from bow A-frame of warping tug.

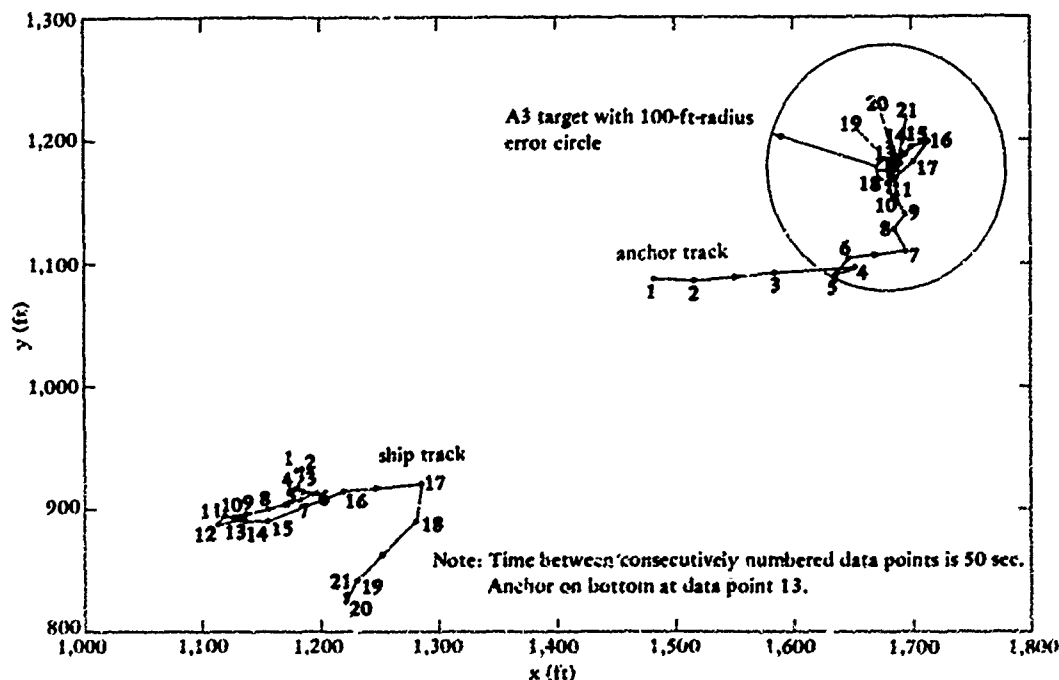


Figure 4-18. ATNAV position data for ship and clump anchor A3 during implant.

To complete Phase VI required about 13 hours as compared to an estimated 11 hours. The extra time required corresponds to that spent in recovering and installing the clump anchor a second time.

#### PHASE VII: ACOUSTIC PROJECTOR IMPLANT

Implant of the two acoustic projectors P1 and P2, as shown in Figure 4-3e, was accomplished on 11 September 1974 after spending 8 days in port to prepare hardware for this phase and Phase VIII. Before proceeding with the projector implant, the umbilical cable from the crown buoy was recovered, and a check was made of all the instrumentation on the structure to insure no degradation had occurred since the last phase. All of the hydrophone stations turned on, and signals were received from all sensors, including the one tension cell that had not responded earlier. The projector pigtails from the crown buoy were recovered, and the three projectors were fired via signals put into the crown buoy umbilical cable.

The weather was excellent, so a decision was made to proceed with the implant.

The electromechanical connection was made between the P1 projector pigtail from the crown buoy and the end of the 10,000 feet of projector cable to be laid out on the seafloor, Figure 4-19 shows this connection being made. The connector was composed of two ends with preformed grips attaching them to the cables, and a center barrel with right and left hand threads to connect the ends together. The electrical conductors were spliced, using the techniques discussed in Chapter 3 and then pushed inside the center barrel. The barrel was rotated to connect the two ends mechanically and then pinned. This connection technique was unsatisfactory because of the very tight fit of the electrical conductors inside the center barrel and the need to rotate the barrel to complete the mechanical connection. It would be very easy for the electrical conductor to rotate with the barrel, thereby destroying the integrity of the connection.



Figure 4-19. Electromechanical connection being made between projector pigtail from crown buoy and 10,000-foot projector cable during Phase VII.

After completing the connection, divers replaced the projector pigtails on the crown buoy and connected strain reliefs to the bottom of the buoy. Using ATNAV for navigation, the warping tug backed away, paying out the projector cable. With 2,900 feet of the cable out, a 200-pound split anchor with a semi-circular groove in each half was placed around the cable and bolted together. This anchor, which was rounded on each end to provide a large bending radius for the cable, held the projector cable away from the crown line and clump anchor to prevent entanglement. The warping tug then resumed backing away while paying out the projector cable. A cable counter that indicated the length of cable paid out was continuously compared to the warping tug distance from the crown buoy. The wire angle also was monitored to insure it remained within bounds. After the 10,000 feet of cable was paid out, the end was terminated to the projector, which was lowered to the bottom on a separate synthetic line (Figure 4-20) with an acoustic release/submersible

transponder in line about 50 feet above the projector stand. The ATNAV positioning system performed well during lowering; the track lines are shown in Figure 4-21. Immediately after touchdown one good projector position reading was obtained, then two bad and one good. The lowering line was then released, although it would have been useful to obtain more readings to better establish the projector position. However, the warping tug was drifting off position, causing concern that the projector stand might be overturned by the lowering line.

The implant of projector P2 followed the same procedure as for P1. Figure 4-22 shows the ship and projector track during the last stage of P2 implant.

Although there was no need to exactly position the projectors, target positions were established to gain operational experience in positioning objects on the seafloor. Projector P1 was placed within about 30 feet of the target and P2 within about 15 feet.

This phase required approximately 12 hours to complete, which compares with an estimated time of 9 hours.



Figure 4-20. Projector stand with projector cable and separate lowering line. Acoustic release/submersible transponder with buoyancy attached is in foreground.

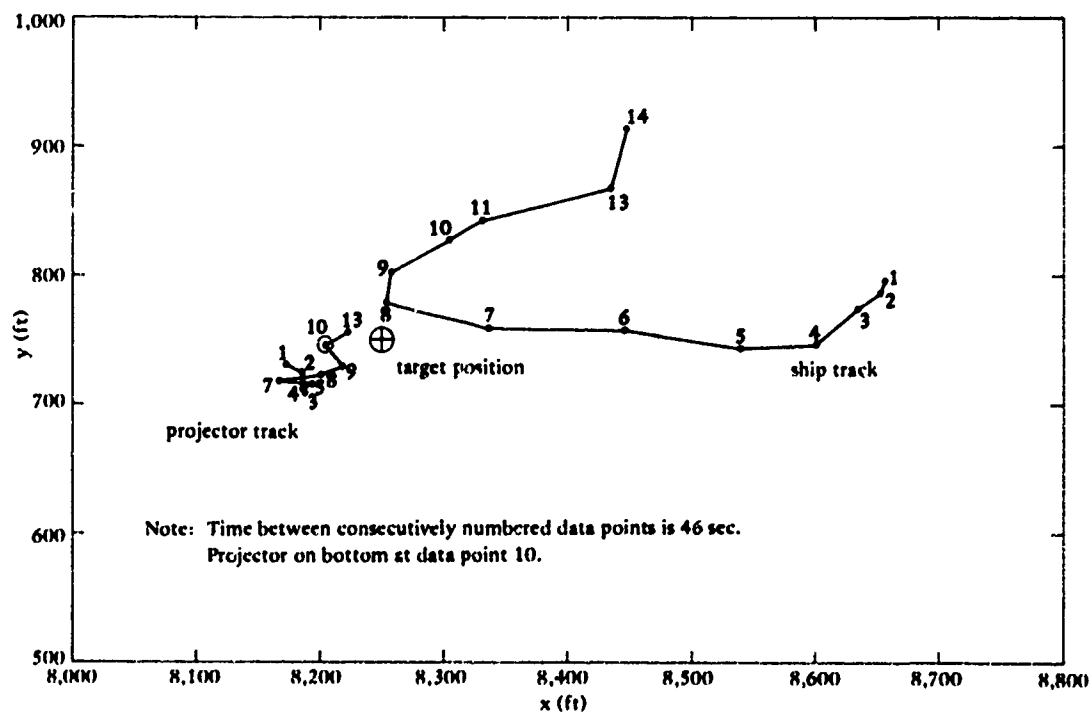


Figure 4-21. ATNAV position data for ship and projector P1 during implant.

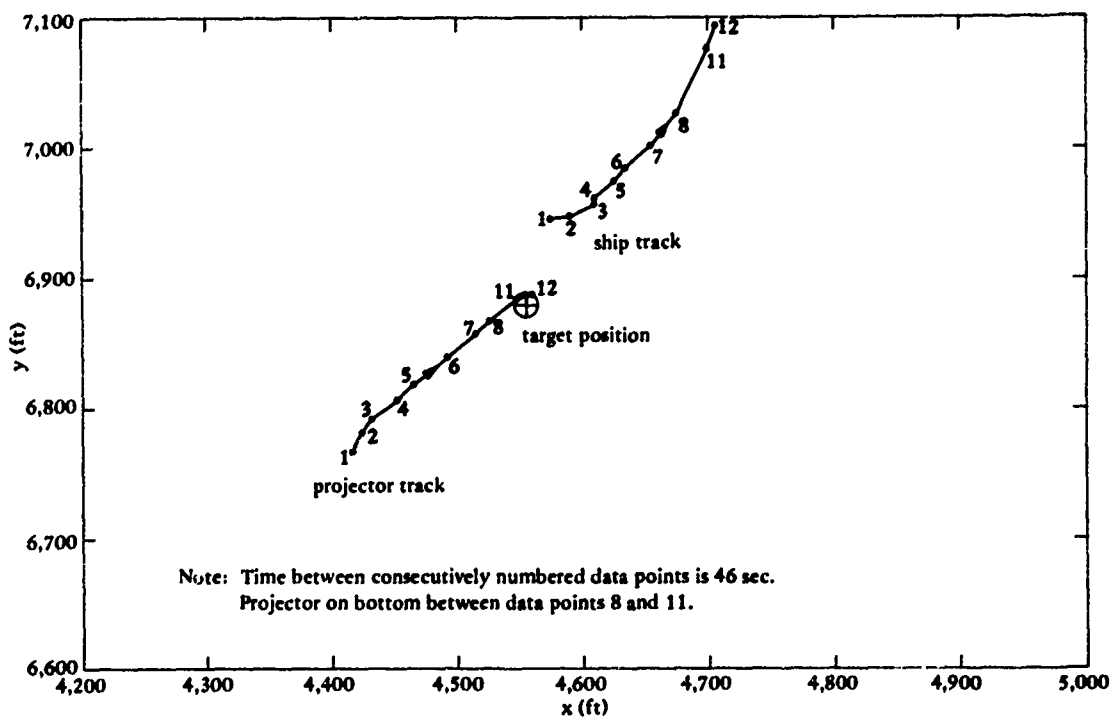


Figure 4-22. ATNAV position data for ship and projector P2 during implant.



Figure 4-23. Dual acoustic release and redundant buoyancy at bottom of current meter strings.

### PHASE VIII: CURRENT METER MOOR IMPLANT

The warping tug moored onsite overnight. At first light, 12 September 1974, the warping tug hauled in the tag line from the construction mooring buoy to the tail line on the grapnel line. A 200-pound Danforth anchor was attached to the end of the tail line. Then, as a last minute change, a 1/4-inch wire was attached to the Danforth anchor with the idea of lowering the anchor while paying out about 1,500 feet of the wire. In this way, the grapnel line would be stretched out on the seafloor to facilitate eventual recovery of the clump anchor. Unfortunately, the 1/4-inch wire was overloaded and parted, letting much of the grapnel line and tail wire fall in a pile on the seafloor.

The operation then proceeded to Phase VIII, the implant of the three current meter strings depicted in Figure 4-3f as CM1, CM2, and CM3.

The moors were deployed anchor first with a dual release and redundant buoyancy located immediately above each anchor (Figure 4-23). One of the releases was also a midwater transponder so that the moor could be accurately positioned during deployment. It was desired to surround the structure with the three moors to detect any significant variability in current magnitude and direction. To do this, the moors were to be positioned 700 feet out from each delta arm on a line perpendicular to the midpoint of each arm. Very careful positioning was necessary to avoid entangling the current meter moors with any part of the SEACON II trimoor. The moors were successfully installed within an average of about 100 feet of their desired locations. The time required to install the three moors with a total of nineteen current meters was 10 hours, which compares closely with the estimated 9 hours [4-1].

### SECTION 3 - DISCUSSION

Several factors share nearly equal importance in the successful implant of the SEACON II trimoor. The thorough planning of the operation was essential, of course. But even in a thorough operations plan it is impossible to foresee and include every detail. The skill, experience, and precruise training of CEL's

riggers who operated the warping tug and implant equipment were equally essential ingredients. The good rapport between the engineers, technicians, diving locker personnel, and rigging crew, which had developed over a long period of working together on numerous projects, resulted in a cooperative team effort that was very effective.

Phasing the implant was very beneficial from several standpoints. First, as anticipated, it provided much flexibility in the operation. The implant atmosphere was quite relaxed because many options were available to the Project Manager and Implant Director depending on weather and the condition of equipment. Retreat to a safe harbor could be made on short notice, while leaving the implanted equipment behind in a protected condition. Because of the smoothness of the operation this option had to be taken only two times: during Phase I when one transponder was installed unbuoyed and the other would not disable on command, and during Phase IV when two of the hydrophone canisters would not turn on. A second benefit of separating the operation into phases was that most of the electronic equipment "soak-tested" in the environment for several weeks during a period when repairs could still be made relatively easily if required. As it turned out, however, no failures were detected during this installation period. By planning rest days between phases, personnel started each implant phase well-rested. This certainly contributed significantly to performance and safety. In fact, no injuries were sustained by any personnel during the entire implant. A safety officer reviewed all plans and was on deck monitoring the safety of all aspects of the operation.

Weather and sea conditions were good to excellent during all phases of the implant. This was not just a chance condition. The period of the year chosen for implant has, on the average, the highest percentage of good weather. Additionally, weather forecasts were obtained starting the day prior to each cruise and were monitored continuously for any changes while at sea. Only one phase had to be interrupted due to adverse sea conditions. The warping tug retreated to port shortly after departure for Phase VI when the swells condition appeared too severe to safely implant the 8-ton clump anchor. One other time, during implant of the last embedment anchor in Phase III, the seas reached the upper limit

of acceptable conditions, but did not prevent successful completion of the phase.

One area of some weakness in the implant hardware was the acoustic transponder navigation (ATNAV) system. As noted in the implant description good position data for the submersible transponders located just above the anchors and projectors were intermittent at some critical times during the implant. There was noise at times in the ATNAV frequency range that caused premature responses from the transponders, thereby resulting in erroneous position calculations. The source of this interference was never discovered. It appeared to be more predominant in the afternoon hours than the morning. Another problem in using the ATNAV system was the sensitivity of the calculated position of the submersible transponder to the velocity of the implant vessel. This was apparent from the scatter in position data obtained even after an anchor or projector was installed on the bottom with the submersible transponder. If accurate ship velocity vectors could have been input into the ATNAV computer, this discrepancy would have been eliminated. It appears repeatability of position is within approximately  $\pm 5$  feet if accurate ship velocity vectors are obtained.

Manual maneuvering of the warping tug to "fly" the anchors and projectors into their desired locations worked relatively well as long as good ship and submersible transponder positions were received regularly. The stern mooring line used during the clump anchor implant also helped significantly in controlling the tug position. Except for A1, which was the first anchor installed using the submersible transponder, all anchors and projectors were able to be placed well within the 100-foot-radius target position. The positions determined for each of the anchors and projectors, which were calculated by averaging several position readings, are believed to be accurate to within a 10-foot-radius circle. Despite some problems in using the ATNAV system, all goals for placement accuracy were met.

The ATNAV system was not satisfactory for determining depth of anchor fluke embedment. As discussed previously, the technique is too dependent on having very accurate water depth data. A small error percentagewise in water depth translates to a large error in embedment depth. A pinger should

have been used as was done during the anchor pullout tests to get direct and reflected pulses which translate into very accurate near-bottom elevation data.

## SECTION 4 - SUMMARY

### FINDINGS AND CONCLUSIONS

1. The SEACON II structure was successfully and safely installed. Key factors in this achievement are believed to be thorough planning; an experienced, well-trained, and compatible implant team; a phased implant procedure; and careful attention to weather conditions.
2. Except for the first one, all anchors and projectors were able to be "flown" in within the desired 100-foot radius of preselected target positions. The measured position data for each of the anchors and projectors are believed to be accurate within a 10-foot radius, which also meets design goals.
3. The ATNAV system was not suitable for determining anchor fluke embedment depth, because the calculated elevation is too sensitive to water depth measurement accuracy as well as other factors.
4. The actual time required to complete each phase at sea was generally about 20 to 30% more than anticipated in the operations plan. However, except for Phase I, each phase was able to be completed within one cruise, and even Phase I was able to be interrupted at a noncritical point.
5. The time between phases was on the average about three times what was anticipated due to the fact that implant was begun before all final outfitting and testing was completed on the system.
6. The adverse effects on electrical equipment due to arc welding of structural components was not adequately considered when determining fabrication procedures. This resulted in damage to one of the acoustic projector cables, which may have had long-term effects on the system not anticipated at the time of implant.
7. The criterion of a single ship implant was met except for using an LCM-8 boat to hold off the crown buoy during Phase VI.



8. Despite the difficulties experienced in using the acoustic transponder navigation (ATNAV) system, all goals for equipment placement accuracy were met.

9. The technique of building a tririg that supports a delta-shaped structure by first installing a two-dimensional trapezoidal moor and then pulling it into a third dimension by adding another leg proved very effective. This permitted the three support buoys and two of the three delta arms to be preassembled, tested, and merely stretched out linearly between the two legs.

10. A last minute change in the grapnel line implant technique and hardware resulted in a failure because inadequate design time was spent on it.

#### RECOMMENDATIONS

1. Any complex ocean construction operation should be thoroughly planned and a comprehensive operations plan should be prepared for controlling the conduct of the operation.

2. To assure the highest probability of success, an implant crew experienced in ocean operations -- one that has worked together on previous operations and one that has received at-sea training for the specific implant -- should be employed.

3. The implant operation should be designed with as many independent phases as possible to provide adequate rest for the crew and contingencies for weather and equipment problems.

4. Weather and sea conditions should be monitored closely, and the reports should be heeded even if some good work days are lost by being conservative.

5. If possible, an operation should be designed to be accomplished from a single vessel to avoid the significant communication and coordination problems posed by multiple vessel operations.

6. The crew should be trained extensively with an acoustic transponder navigation system at the planned implant site to determine all of the idiosyncrasies of the equipment.

7. A pinger system rather than a transponder navigation system should be used to obtain accurate data on elevations of equipment near the bottom.

8. All possible adverse effects to electrical equipment due to arc welding on or near associated mechanical equipment should be evaluated.

9. Spur-of-the-moment changes in hardware or techniques during an at-sea construction operation should be avoided.

10. In conducting an ocean construction operation, as many of the electrical components as feasible should be preassembled and tested to minimize making at-sea electrical connections and splices.

## CHAPTER 5

### MAINTENANCE, REPAIR, AND RECOVERY OF STRUCTURE

#### INSTRUMENTATION STATUS AFTER IMPLANT

Within 1 week after implant of the SEACON II structure, the fishing vessel *La Vida*, under contract to CEL, was moored at the crown buoy for several days in a joint cruise with NUSC, New London personnel. During the cruise the SEACON II instrumentation system was checked out, and NUSC made measurements on the dynamic response of the delta arm between node buoys NB1 and NB2.

The major findings of this cruise were that all equipment appeared to be operating properly except for three of the five tension cells and the three acoustic projectors. The problem with the tension cells is discussed in Chapter 3. Two of the projectors appeared to have open circuits, and the third had a 2,000-ohm short to seawater. The nearly shorted projector operated, but there was concern that electrolysis would quickly fail the electrical conductor.

#### PROJECTOR REPAIR CRUISE

On 9 October 1974 a cruise was conducted aboard the warping tug to make repairs to the projectors. Since it was not known exactly where the problems were located, the contingency plan included the recovery of the projectors themselves, even the one on the clump anchor if necessary.

The troubleshooting began at the crown buoy, the easiest location to get to and the most likely spot for some of the problems. The ATNAV system was used to position the tug over the crown buoy, which was lifted under the A-frame, as shown in Figure 5-1. The short in the projector cable was found at the spot that had received a welding arc during preparations for Phase VI of the implant. This section was cut out, and the bitter ends of the cables were spliced. The two open circuits were located where field-installable boots, which form the female half of single-pin connectors, had been used. These connectors were bypassed by using the field-splicing technique developed for SEACON II.

At the completion of this cruise all three projectors operated. However, within a week, projector P1 had failed again.

#### UNDERWATER SPLICING REPAIRS

During the period 23 through 29 October 1974 the fishing vessel *La Vida* was again at the site for a combined data taking cruise with NUSC personnel. On 26 October *La Vida* was moored to the crown buoy, and the crown buoy umbilical was taken aboard. Without warning the mooring line parted at the crown buoy, and the umbilical was broken off at the crown buoy junction box before it could be placed overboard. Although there was a backup umbilical, the bare wires at the junction box were all shorted to seawater and each other.

Thus began a year-long effort to correct this problem. It was decided not to resurface the entire crown buoy as was done in the initial repair, because an inspection by the manned submersible *Turtle* after that cruise showed the projector wires to be piled up near the clump anchor. It was felt the projector cables on the bottom could possibly be cut if the clump anchor with its protruding metal skirt was set down on them. Instead, the first attempts involved clamping oil-filled bladders and tubes over the stub on the junction box umbilical penetrator. Some residual seawater always remained, causing the shorting problem to continue.

On 19 November the fishing vessel *La Vida* returned to the site for another joint cruise with NUSC personnel. During this cruise CEL divers cut the seven electrical conductors from the crown line to the junction box, removed the junction box, and brought it on board the fishing vessel with the projector cables still attached to it. The damaged penetrator was isolated by disconnecting the wires which ran to it inside the oil-filled junction box. The junction box was then reinstalled.

The seven electrical cables were then spliced by divers using the AMP dielectric rubber sealant in a

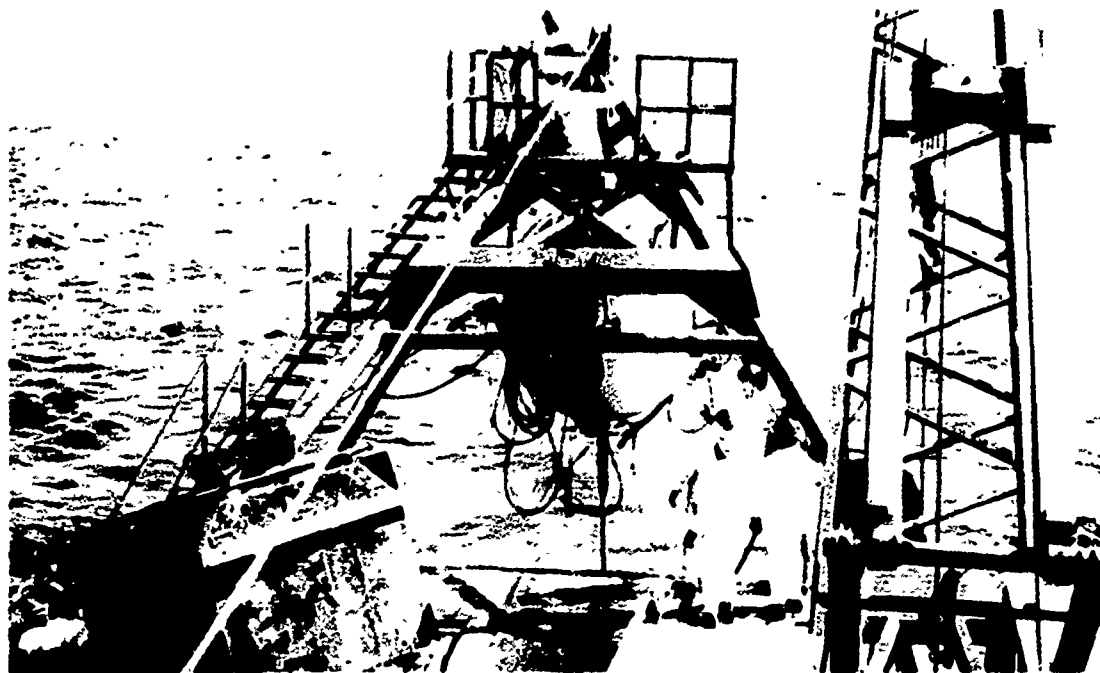


Figure 5-1. Crown buoy hauled in under warping tug A-frame for projector cable repair.

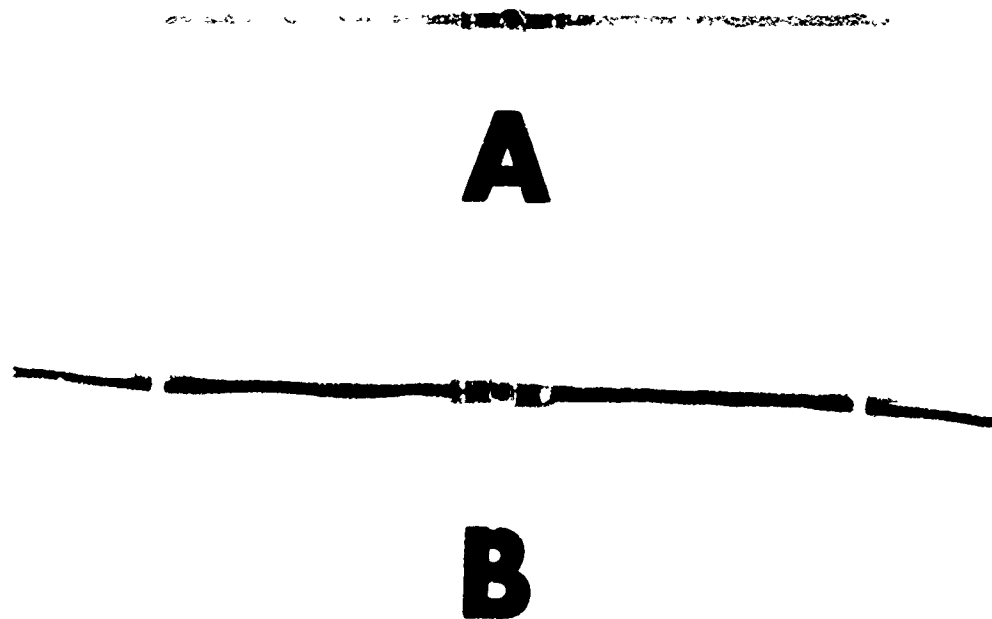


Figure 5-2. Butt connector centered within 6-inch nylon tube. Before (A), and after completion (B).

method similar to the one developed for field splicing in air. Initially these splices operated. However, after several days in service, apparently the small amount of entrapped seawater at the electrical junctions caused corrosion which resulted in loss of a good metal-to-metal connection and, therefore, electrical continuity.

Failure of the AMP sealant technique resulted in a series of attempts with crimp-type connectors. After numerous attempts the technique reported on in Reference 5-1 was found to be successful. Essentially the technique involves centering a crimp-type butt connector inside a nylon tube about 6 inches long (Figure 5-2). Both ends of the tube are filled with 3140 RTV, which is a silicone base rubber with a noncorrosive alcohol solvent. Divers place the ends of the wires in each side of the splice and crimp the connector. Apparently the RTV wipes the water from the wires as they are inserted, seals out the seawater, eliminates air voids, and provides a pressure-balanced connection.

As discussed in Chapter 3, on 9 December 1975, 13 underwater electrical splices were successfully made with the technique described above. The junction box was completely bypassed, and seven electrical conductors from the crown line and six from the two outboard projectors, P1 and P2, were spliced directly to the umbilical cable.

The cable to projector P1 that had not operated for a year was recovered and cut off below the point where the 250-foot projector pigtail connected to the 10,000-foot projector cable. The projector was able to be fired from this bitter end, so a new section of cable was spliced in to get P1 operable again.

Inspection of the wires at the connection between the 250-foot pigtail and the 10,000-foot projector cable revealed the cause of the short. The one long armor wire, shown in Figure 5-3, had accidentally stuck into the center electrical conductors, breaking through the insulation on one wire and causing it to short. This apparently occurred during the process of fitting the splice inside a barrel that connects the two mechanical terminations shown in Figure 5-3. A discussion of the difficulty experienced in making this connection was presented in Chapter 4.

## SUBMERSIBLE OPERATIONS

### Manned Submersibles

The Navy's SUBDEVGRU 1 manned submersible *Turtle* operated at the SEACON II site on 25 to 26 October 1974. During one dive an attempt was made to attach a buoy to the one transponder that had been implanted without one. The transponder was located with the aid of the ATNAV system, but the sub was unable to get the buoy attached due to a snap hook being fouled with the line to the buoy.

On 26 October *Turtle*, with a submersible ATNAV transponder attached, attempted to occupy a position near the clump anchor. Updated position data were needed because the clump anchor had been moved during the projector repair cruise. While maneuvering, *Turtle* became temporarily entrapped under leg L3. Once free, she surfaced with orders not to venture near any of the cables or anchors on future dives.

During a later operation at the site, *Turtle*'s sister vehicle *Seaciff* successfully recovered the unbuoyed transponder along with another transponder that had batteries too weak to activate the release.

### Unmanned Submersible

NUC's *Curv III* vehicle operated at the SEACON II site from 11 to 14 November 1975. The primary objectives of the cruise were to determine embedment depths and positions of the two embedment anchors and to recover a buoyant riser cable from node buoy NB1 which was used in the NUSC portion of the experiment. Problems with *Curv III*'s umbilical cable and the ATNAV positioning system severely limited the time available to do useful work. The embedment depth of anchor A2 was accurately determined, and the NUSC tether was removed. The other goals were unable to be met.

## STRUCTURE RECOVERY OPERATION

On 12 May 1976, after nearly 22 months in the water, the SEACON II structure, consisting of some

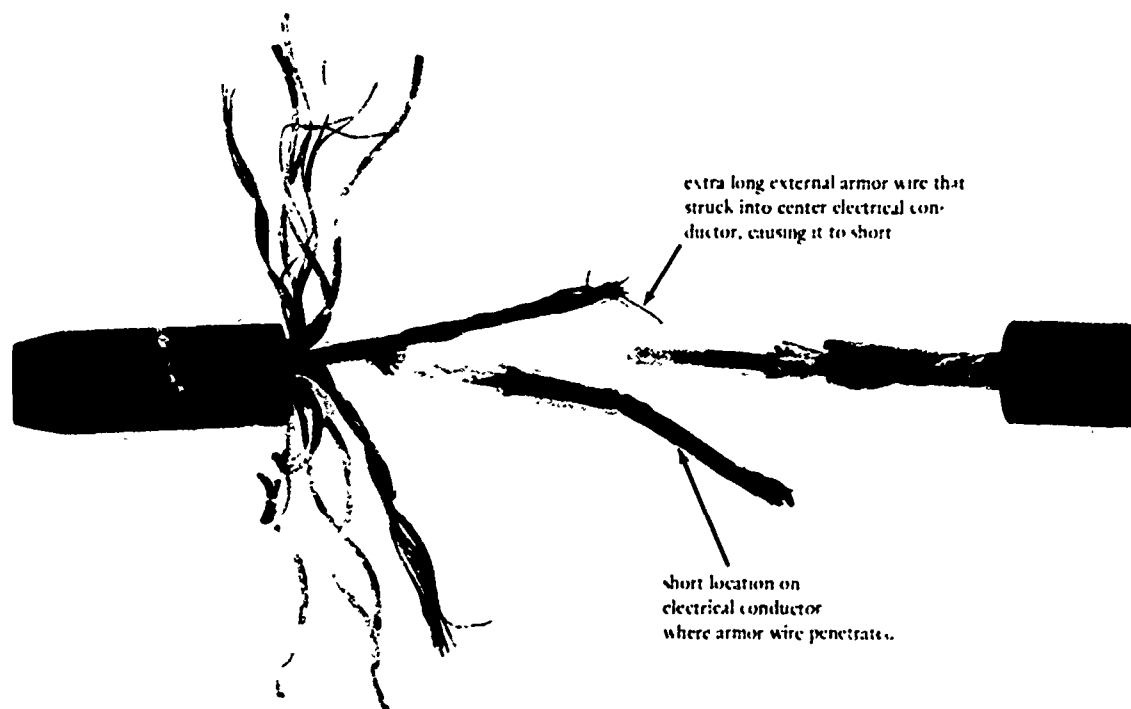


Figure 5-3. Electromechanical connection between projector cables, showing cause of fault in P1 projector cable.

30 tons of hardware, was recovered aboard the CEL warping tug with the LCM-8 boat and CEL divers assisting. The operation began with divers attaching a lift line to a wire strap that had been connected to the top of the crown line by U-clamps during an earlier cruise. Once the clump anchor was on board, the recovery proceeded generally in reverse of the implant procedure but much faster. The total recovery operation was completed in 16 hours.

The corrosion and fouling analysis of the structure is provided as Appendix A. Discussion of the performance of specific equipment, such as the anchors, cables, tension cells, etc., is included in Chapter 3.

#### FINDINGS AND CONCLUSIONS

1. Techniques for making repairs to and performing maintenance on an undersea cable structure were

demonstrated using surface vessels, divers, and manned and unmanned submersibles. Most of the jobs undertaken were successfully completed but with considerable difficulty.

2. Materials and techniques for diver-splicing of single- and multiconductor cables underwater were successfully developed and demonstrated.

#### RECOMMENDATIONS

1. Manned submersibles should avoid working in the vicinity of cables even if they are under tension as leg 1.3 was.
2. The techniques developed for diver-splicing underwater are recommended for use in situations where splices cannot be made in air.

## CHAPTER 6

### COMPUTER PROGRAM VALIDATION

#### SECTION 1 - INTRODUCTION

In this chapter, the data obtained during the SEACON II experiment to validate a steady-state computer program are discussed and results of measured and computer-program-predicted SEACON II structure response are presented. A description of the computer program being validated is provided along with a description of the input required to successfully use the program and an explanation of how to interpret the program output.

Measured and predicted results are compared over eight tidal cycles. These results are accompanied by a discussion section to give the reader a clear picture of the present status of the computer program validation effort. Finally, conclusions and recommendations are provided to help guide future efforts in this area.

#### SECTION 2 - DESADE COMPUTER PROGRAM

##### OPERATION

The computer program currently being validated with the data obtained from the SEACON II experiment is called DESADE and was developed at the Naval Research Laboratory by Dr. R. A. Skop [6-1]. DESADE is a steady-state program that is based on a finite element representation of the structural cables. It utilizes a technique called the Method of Imaginary Reactions (MIR) to make complex, redundant structures, such as SEACON II, determinate. In MIR, redundant constraining reactions at the anchors and at any internal points where a redundancy occurs are cut from the structure and are replaced by equilibrating imaginary reactions placed at the free (cut) ends of the cables. Once the structure has been made structurally determinate, the zero current equilibrium position of succeeding cable elements is calculated

until the free ends are reached. Overall, the procedure is an iterative one in which new corrective forces are applied to the cable ends each time their position does not agree with the calculated position of a junction in the structure or with the actual position of the anchors. The iterations continue until the discrepancy between the position of cables ends and their associated junctions or anchors is less than a prescribed amount.

When currents are applied to the structure, MIR is combined with a successive approximation procedure so that, for each MIR iteration, new hydrodynamic forces based on the present structure configuration are calculated and applied to each cable element. This procedure continues until the equilibrium coordinates of the structure for two successive iterations differ by less than a preselected fixed amount; a solution has then been achieved.

A listing of the basic DESADE program is available in Reference 6-1. A listing of DESADE modified to accept current data, which varies in magnitude and direction with depth, can be obtained from CEL.

##### CAPABILITIES

As presently programmed, DESADE can be used for the static analysis of multicable (up to 22 cables), three-dimensional structural arrays. The mechanical properties of inextensible elements, synthetic lines, or wire rope can be assigned to the cables. In addition, any number of discrete in-line devices, such as electronic instruments or buoys, can be included in the analysis. These capabilities are complimented by the ability to include in the analysis current profiles that vary in magnitude and direction with depth.

##### LIMITATIONS

While the DESADE program is very general, in its present form it does have certain limitations. First, no

Table 6-1. Summary of Measurement Accuracy of Components

Parameter	Measurement Accuracy of -		
	Buoys	Cables	Discrete Devices
Size			
Diameter	$\pm 0.02$ ft	$\pm 0.003$ in.	-
Length	-	$\pm 1.0$ ft (legs) $\pm 0.25$ ft (arms)	-
Length/diameter	-	-	$\pm 0.01$ ft
Weight/buoyancy	$\pm 12$ lb	$\pm 0.003$ lb/ft (legs) $\pm 0.009$ lb/ft (arms)	$\pm 0.2$ lb
Hydrodynamic drag coefficient	$\pm 0.05^a$	$\pm 0.06^b$	$\pm 0.05^a$

<sup>a</sup>Values based on  $C_d$  curves of idealized spheres and cylinders.

<sup>b</sup>Nonstrumming drag coefficient. Amplification factors for strumming cable are approximate.

cable can lie on the seafloor, and, under the action of applied forces, no cable segment can have zero tension. Second, all structural components must be totally submerged, or the position of the components at the surface must be specified with x, y, and z coordinates. Third, the size of the discrete elements on the cables must be small compared with the overall dimensions of the array. Finally, only normal drag forces are applied to the cables; tangential drag forces on the cables and lift forces on discrete elements are assumed to be negligible.

#### INPUT DATA TO DESADE PROGRAM

The data required as input to the DESADE program consist of physical and hydrodynamic characteristics of structure components, including the position of restraining anchors and the characteristics of the environment in which the structure is

deployed. The physical properties define the size, shape, weight (buoyancy), and position of all structural components and devices on the structure. For SEACON II, all the components were carefully measured and weighed with balance scales in freshwater of known density. All submerged weights or buoyancies were then converted to reflect the seawater conditions found at the SEACON deployment site. Table 6-1 is a summary of the measurement accuracies for the major components.

The hydrodynamic data define the drag characteristics of the structural components and devices. In the discussion portion of this section, details on how drag coefficients were determined for the cables when exposed to ocean currents are described.

The environmental data required for DESADE consist of the density of the seawater at the SEACON II deployment site and a detailed representation of the current regime impinging on the structure.

The input deck consists of the cable array source deck (the physical and hydrodynamic properties of the structure) and the current information. A listing of the source deck and the current information for tidal cycles 1, 2, and 3 can be obtained from CEL. These data can be used with other computer programs, the output of which can then be checked against the measured and predicted response of SEACON II as presented in the Results section.

#### OUTPUT FROM DESADE PROGRAM

The output from DESADE consists of a listing that describes (1) the physical characteristics of the cable structure, (2) the equilibrium position of the structure for the zero current case in terms of cable tensions, cable angles, and x, y, z positions of selected points on the structure, and (3) the equilibrium position for the structure in terms of cable tension and angles when exposed to various current regimes of interest. A listing of DESADE output for tidal cycle 1 is available from CEL.

### SECTION 3 - RESULTS

Two types of results are of interest: zero current results and results when currents are acting on the structure. Zero current results are important, because, by comparing the measured and predicted data for this condition, it is possible to (1) perform a preliminary check on the computer program before the hydrodynamic forces are applied, and (2) reduce some of the systematic errors in the predicted data due to inexact knowledge of the physical characteristics of the structure and in the measured data due to instrumentation calibration errors, etc.

Results obtained while the structure is exposed to ocean currents are of interest, because it is the response of the structure to ocean current regimes that is of importance to structural designers. These results are generally most important from a relative standpoint, i.e., on the basis of the relative change in structure position from data point to data point over time.

#### ZERO CURRENT CASE

A survey of the current data showed that, even between tidal cycles when the currents generally slacken, there was always some current activity at the SEACON II deployment site. However, the data did show a number of occasions when the currents were very low (5 cm/sec or less over the entire structure); these low current situations were used in lieu of actual zero current conditions to make initial checks of the program and to adjust the anchors' positions to achieve a good "zero current" fit between the measured and predicted data.

When zero current comparisons were initially made, a nearly constant bias of several tens of feet between the measured and predicted data was noted. This bias was felt to be caused by errors in the anchor position information used as input to the DESADE computer program. Because the bias occurred repeatedly when both zero current and current conditions were compared, it was decided that more precise information about the position of the anchors was required.

An in-situ inspection of the structure was made

with the Naval Undersea Center *Cuv III* inspection vehicle. It was found that anchor A1 had not penetrated the seafloor nearly as far as originally estimated (estimated, 25 feet; direct observation, 7-1/2 feet), and, therefore, the effective position of the anchor (the point where the cable passes through the seafloor/water interface) was somewhat in error.

Prior to deploying the *Cuv III* vehicle for the inspection, it was equipped with an acoustic transponder so that its position during the inspection could be tracked with the SEACON ATNAV position system. It was hoped that when the vehicle occupied the anchor positions during the inspection, precise anchor position data could be obtained. However, shadowing effects caused by undulations in the surrounding seafloor made it impossible to get a fix on the new position of the anchor or to confirm the position of the point where the embedment anchors penetrated the seafloor. In addition, the *Cuv III* cruise had to be terminated before an assessment of conditions at the second embedment anchor, A2, could be made.

When leg 1.2 was retrieved during structure recovery, it was found that the launch vehicle for the embedment anchor, which had not released from the leg, was acting as the anchor and had, thereby, effectively eliminated all of the 75-foot anchor pendant from acting as part of the structure. With this new information the position of the anchors was redefined and the zero current position for the structure was recalculated using DESADE. Accordingly, the bias was reduced but not completely eliminated as shown in Figure 6-1. Using the positions of acoustic nodes B and D at the corners of the delta as a guide, the majority of the bias was removed by shifting the anchor positions until the measured and predicted results at B and D were within approximately 5 feet of each other. No attempt was made to obtain a closer fit between the measured and predicted results, because the measured position data had to be interpolated to obtain a match between position measurement times, and because a significant current (more than 5 cm/sec) might be present between the current meters that could go undetected and, thus, shift the position of the structure.

Nodes B and D were chosen to guide the anchor position changes as these positions are based on precise data from three projectors on the seafloor,



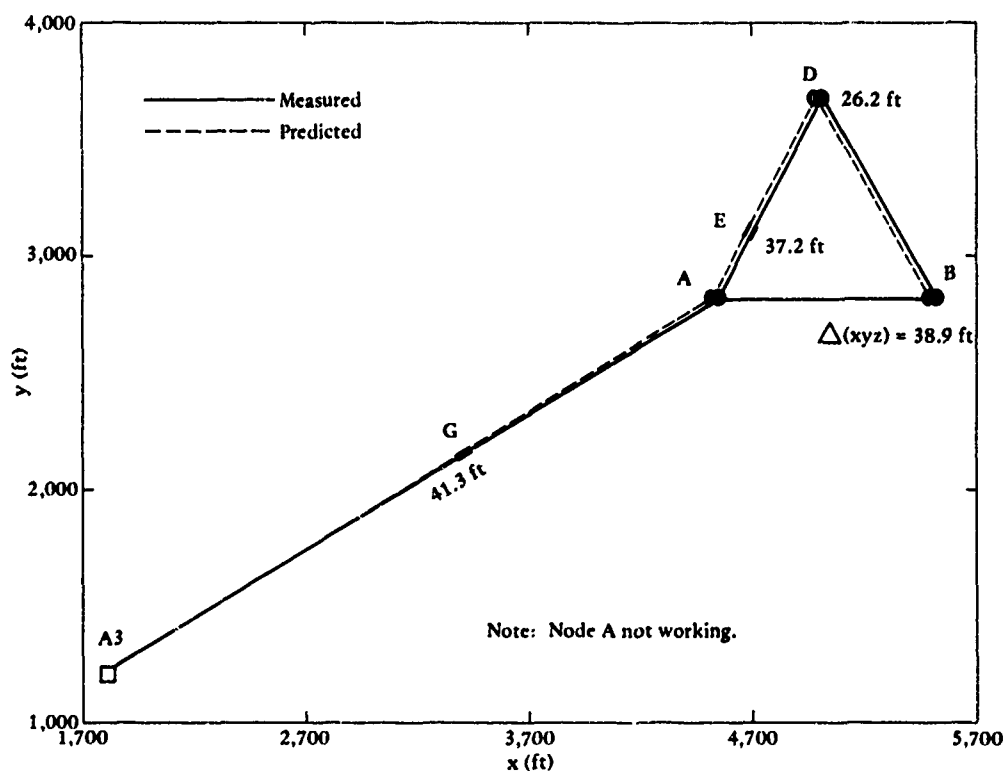


Figure 6-1. Measured and predicted zero current positions before anchor position adjustments.

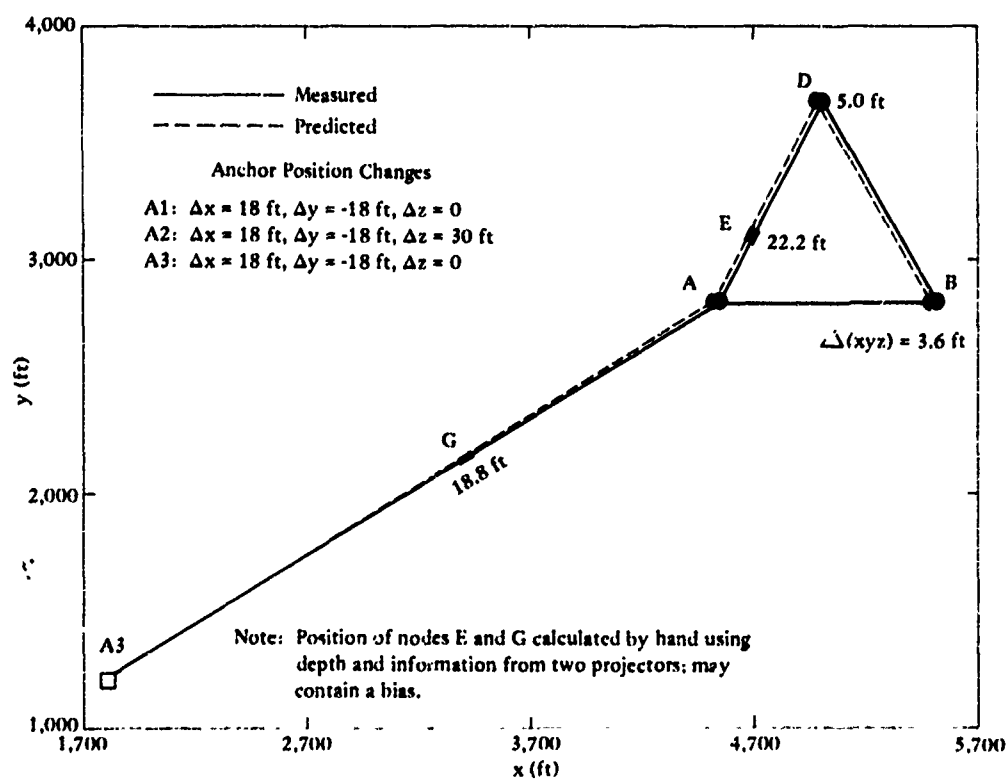


Figure 6-2. Measured and predicted zero current positions after anchor position adjustments.

whereas the positions of nodes E and G were calculated using information from two projectors and a depth meter at the node. This calculation is quite sensitive to depth errors and, therefore, was judged not suitable to guide the anchor position adjustments. The anchor position changes required to achieve the match situation are shown in Figure 6-2, along with the new total differences between measured and predicted results for the zero current condition. The anchor position changes in all cases are within the bounds of accuracy set for them.

### CHANGING CURRENT CASE

#### Tidal Cycles

Once the structure had been "zeroed" to remove the major systematic errors and the majority of the bias, computer runs were made for eight tidal cycles. For tidal cycle 1, the measured and predicted responses of four acoustic nodes on the structure to the changing current regime are given; the nodes are those designated as B, D, E, and G on Figures 6-1 and 6-2. For the remaining seven cycles, the measured and predicted response of acoustic node B is provided. The response of this node was found to be representative of the response of all nodes on the delta portion of the structure, and it provides a basis for comparing the differences between measured and predicted results.

#### Drag Coefficient

Before beginning a discussion of the measured and predicted results obtained over the eight tidal cycles, a brief description of the process required to determine the correct drag coefficient for the cables is given. When the SEACON II structure was being designed, a normal drag coefficient of 1.2 for the cables was selected for use in the DESADE program. When the measured data began coming in from the SEACON II experiment, and initial comparisons were made between measured and predicted results (see Figure 6-3), it became clear that this drag coefficient was too low when the current velocity on major portions of the structure was more than 7 or 8 cm/sec. The predicted response of the structure at the

acoustic nodes was much less than the measured data indicated it should be. With this in mind, it was decided that a larger drag coefficient should be tried; a drag coefficient of 3.0 was selected. When results from this computer run, also shown on Figure 6-3, were compared with the measured data, it could be seen that the predicted structure response was much greater than the measured data indicated it should be except for that portion of the cycle beyond 0520 hours. For this portion of the curve, the currents are decreasing in magnitude from 10 to 12 cm/sec at 0520, to 9 to 10 cm/sec at 0620, to 5 to 6 cm/sec at 0720. Beyond 0720 there is a general trend toward decreasing velocity magnitude down to 4 to 5 cm/sec. The current regime between times 2320 and 0520, where neither the  $C_d = 1.2$  or  $C_d = 3.0$  curves even come close to matching the measured data, is characterized by velocities of from 10 to 18 cm/sec near the elevation of the delta with generally lower velocities occurring as the depth increases.

At this point it was decided that additional insight into the drag coefficient for the SEACON II cables was required. A short section of the cable was sent to the Naval Postgraduate School at Monterey, California, so that drag tests could be performed in the NPGS water tunnel. The results of these tests are shown in Figure 6-4 along with results obtained from an earlier test performed at the Naval Ship Research and Development Center (NSRDC) on a 15-foot section of the SEACON II cable and drag results obtained by others on smooth, circular cylinders and stranded cables. From this figure it can be seen that the NPGS results for the SEACON II cable parallel the smooth cylinder and stranded cable data, but have an average value for drag of 1.55 over a Reynolds number range of from 800 to 8,000. For the same range of Reynolds numbers, the smooth cylinder data averaged 1.0 and the stranded cable data averaged 1.25. The NSRDC data show large variations in drag coefficient for small changes in Reynolds number; this was the result of cable strumming.

Early in the SEACON II structure design process, a state-of-the-art analysis of the cables for the conditions expected at the SEACON II site indicated that cable strumming should not occur in the structure. Since that time, new analysis procedures and associated computer programs have been developed

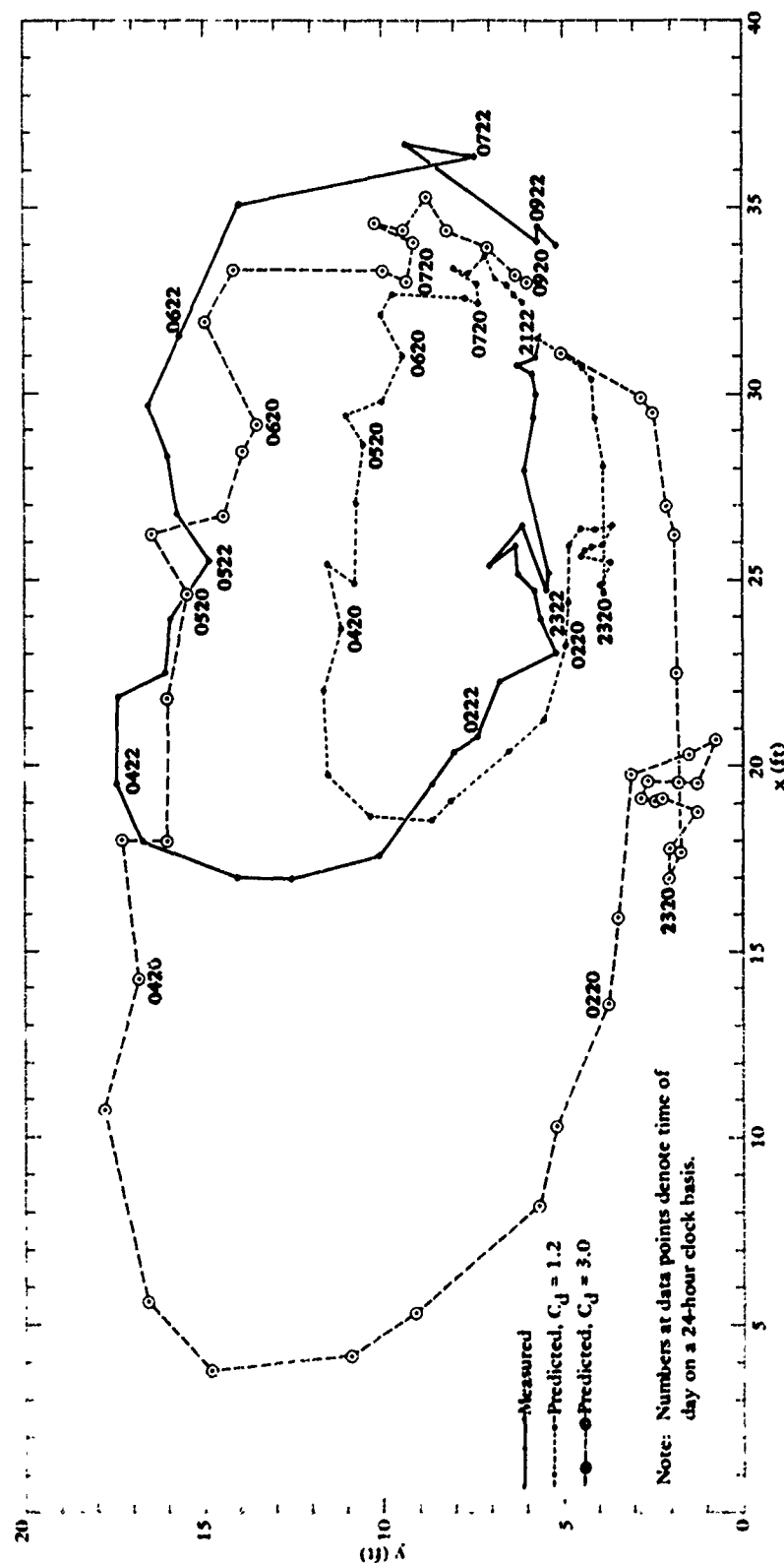


Figure 6-3. Displacement of node B during tidal cycle 2.

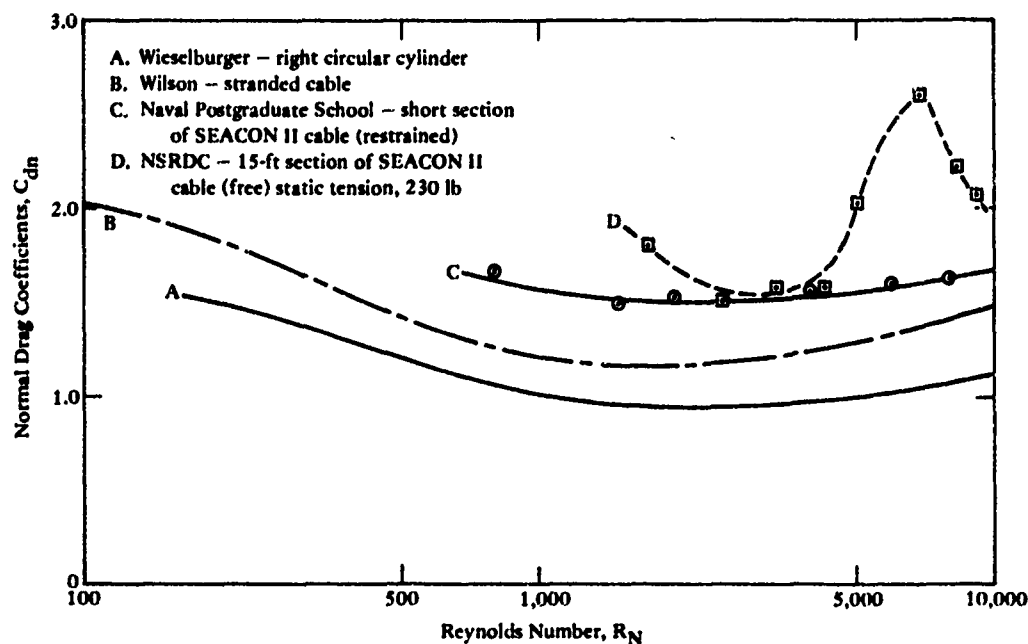


Figure 6-4. Normal drag coefficients for cylinder, stranded cable, and SEACON II cable.

by R. A. Skop at the Naval Research Laboratory that can more precisely predict if strumming will occur in a given cable. Based on the predicted character of the strumming, i.e., its frequency and amplitude, drag coefficient amplification factors can be assigned to account for the attendant increase in drag [6-2]. While these procedures are at this point approximate and can only be utilized where the current is uniform over the length of the cable, which for SEACON II means the cables on the delta portion of the structure only, they do represent the best available means for predicting the presence and effects of cable strumming and were felt to be a necessary addition to the validation of the DESADE program.

The physical properties of the delta cables and the discrete devices on the delta cables along with the current information at the elevation of the delta were used to determine strumming frequencies and amplitudes. These in turn were used to generate drag coefficient amplification factors and drag coefficients for the delta cables. The leg cables were assigned constant drag coefficients of 1.55, although it was felt that at least the upper portions of these cables were also strumming.

Figure 6-5 illustrates how the normal drag coefficient varies with Reynolds number based on normal velocity for arm D23 (between NB2 and NB3). This figure shows that, according to the analysis technique, cable strumming will occur in arm D23 at Reynolds numbers greater than approximately 100 and will produce increased but fluctuating drag coefficients. Cable strumming begins when the fundamental frequency for the cable matches the Strouhal frequency for the cable. As the Reynolds number increases, there is a reduction in drag coefficient, until the second modal frequency is reached, where again the drag coefficient jumps to a high value. This trend continues with a general overall increase in values for drag. For arm D23, the drag coefficient is predicted to be more than 3.0 when the Reynolds number based on the normal component of velocity is greater than 600. The drag coefficient data presented in Figure 6-5 and similar data for the other two cables of the delta were the predicted response of the structure.

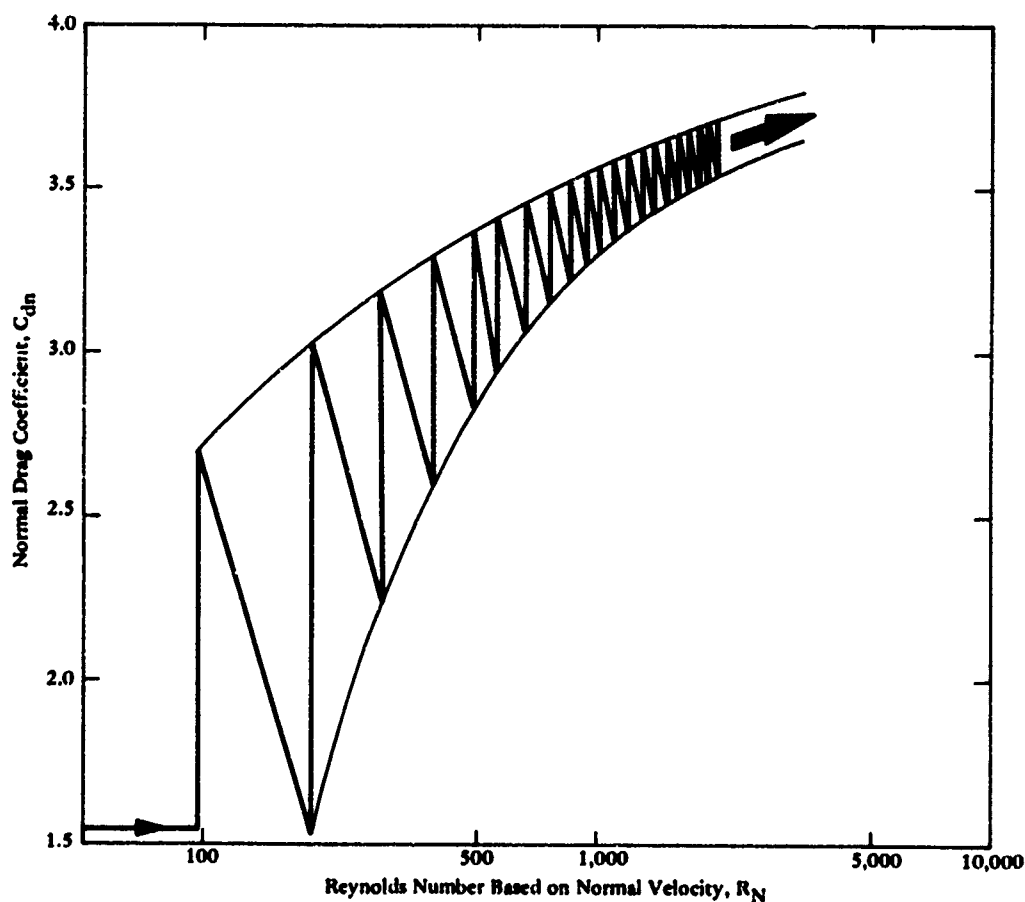


Figure 6-5. Predicted variation in normal drag coefficient for arm D23.

#### Current Profiles

For tidal cycles 1 through 8, the current profiles change with time to reflect the ebb and flow of the tidal conditions at the site. Most of these cycles begin with flow in a westerly direction at a velocity of 3 to 5 cm/sec, which builds to a velocity of 12 to 18 cm/sec over the first hour or two of the cycle. Shortly after this buildup, the direction changes toward the north, until over the next few hours of the cycle it has moved to a north to north-east direction. Toward the end of the cycle, the current begins to recede, until it finally reaches a velocity of 3 to 5 cm/sec and generally has a strong south or west component.

Over the depth of the structure, the current profiles have greatly varying character from cycle to cycle. Figures 6-6 through 6-13 summarize the current data for the eight cycles using vectors to illustrate the current magnitude and direction changes over time and over the depth of the structure. The vectors are based on hourly data from eight\* current meters at the elevations shown on the figures. The presence of shear layers in the current data can be detected on these figures by observing the direction and magnitude of the vectors at a specific point in time (noted by vector numbers) at the various elevations. A large increase in vector length or large vector direction change between adjacent current meters indicates a shear situation exists.

\*Eleven current meters were deployed with double meters at 2,410- and 2,510-foot elevations. Meters at 2,510, 2,110, and 1,410 feet failed. The 2,410-foot data are the average of two meters. The elevations are heights above the 2,910-foot level, which corresponds to the origin of the z-axis for DESADE.

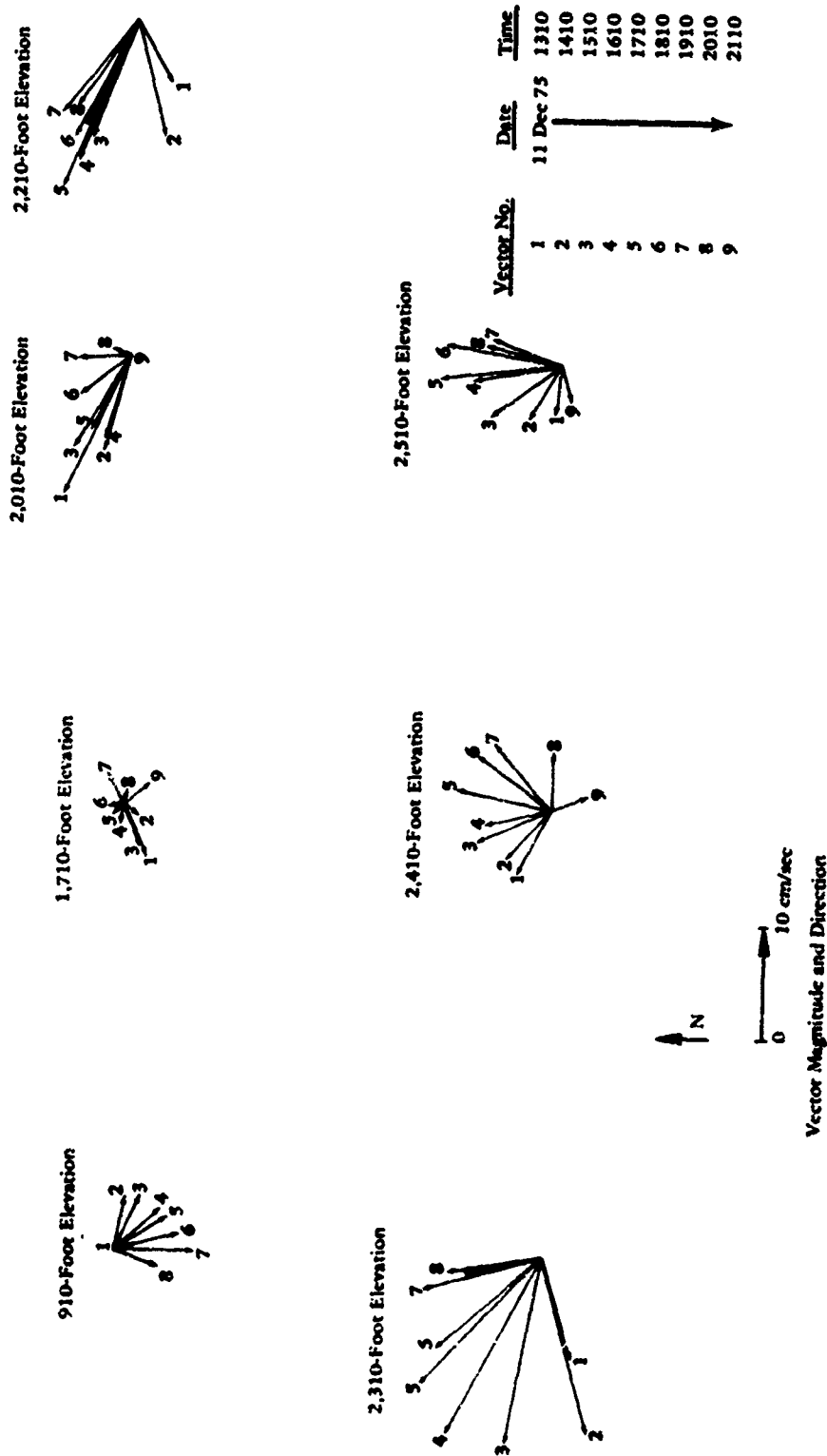


Figure 6-6. Current vectors for tidal cycle 1.

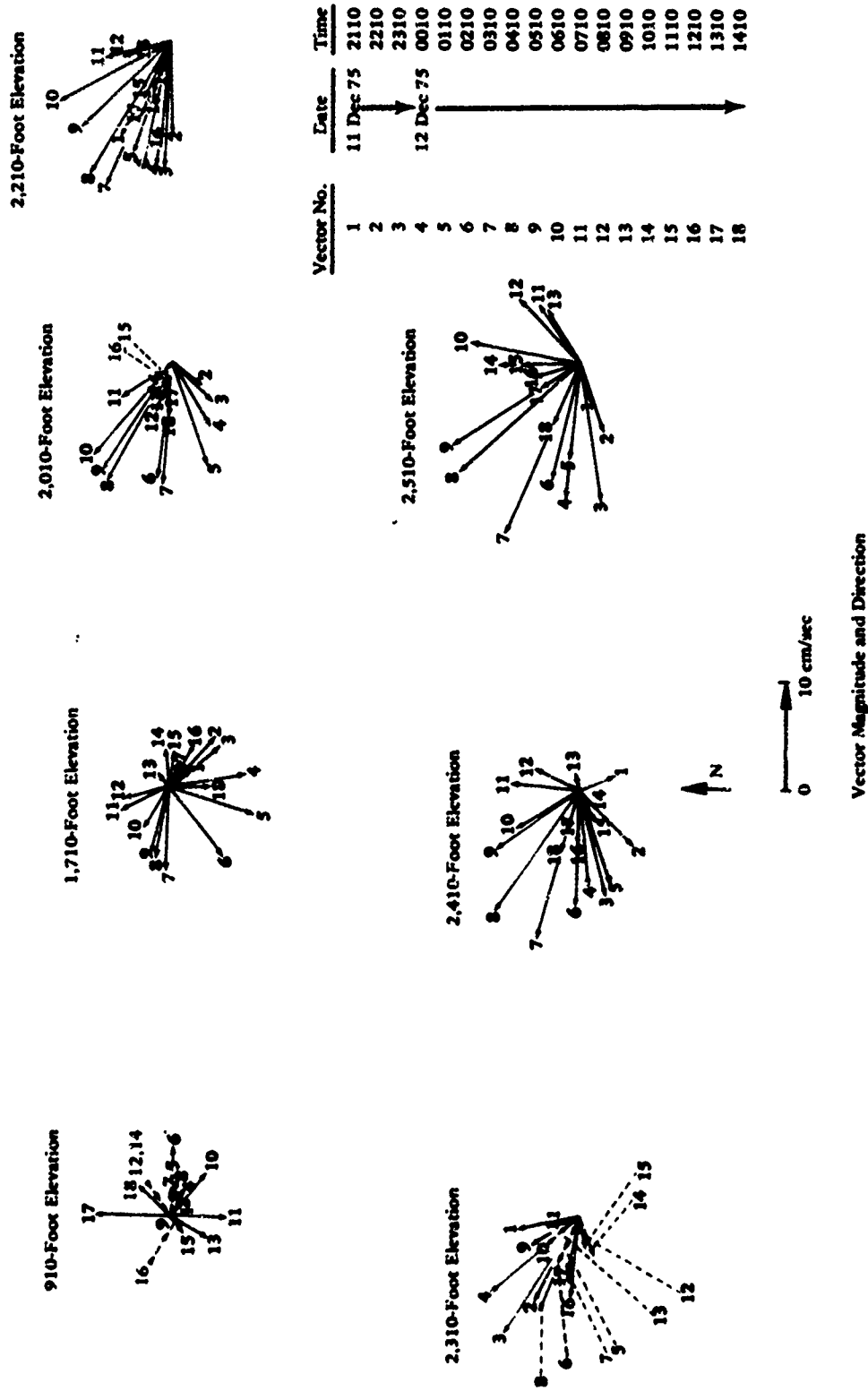
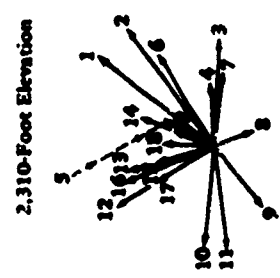
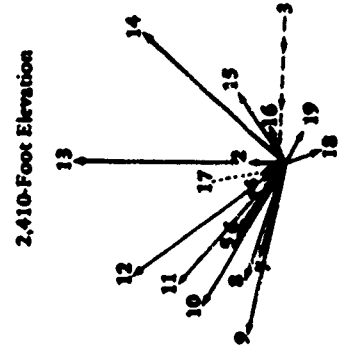
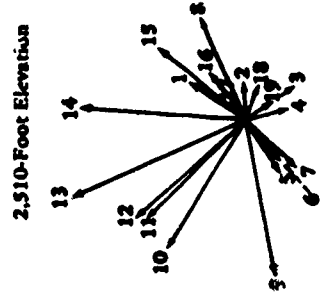
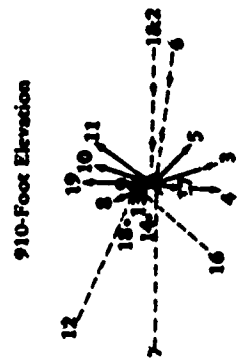
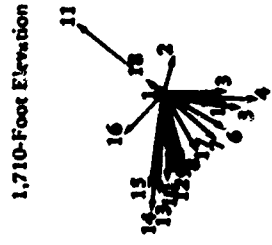
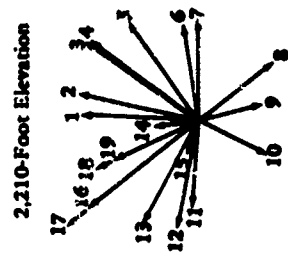


Figure 6-7. Current vectors for tidal cycle 2.



Vector No.	Date	Time
1	16 Dec 75	1010
2		1110
3		1210
4		1310
5		1410
6		1510
7		1610
8		1710
9		1810
10		1910
11		2010
12		2110
13		2210
14		2310
15	17 Dec 75	0010
16		0110
17		0210
18		0310
19		0410

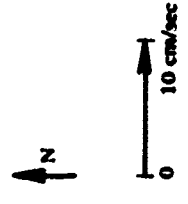
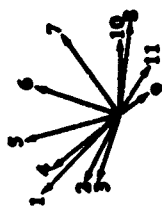


Figure 6-8. Current vectors for tidal cycle 3.



2,210-Foot Elevation



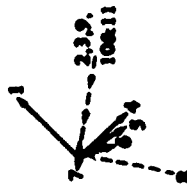
2,010-Foot Elevation



1,710-Foot Elevation

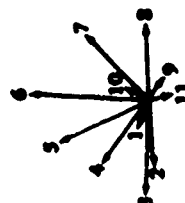


916-Foot Elevation

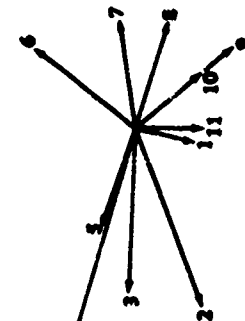


Vector No.	Date	Time
1	17 Dec 75	0510
2		0610
3		0710
4		0810
5		0910
6		10:0
7		1110
8		1210
9		1310
10		1410
11		1510

2,310-Foot Elevation



2,510-Foot Elevation



2,410-Foot Elevation

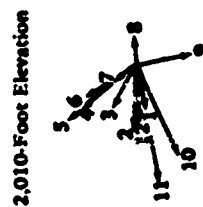
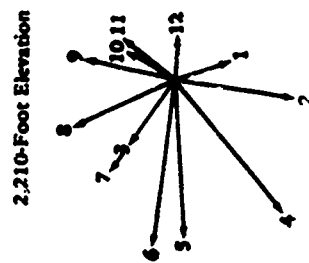


N

0 10 cm/sec

Vector Magnitude and Direction

Figure 6-9. Current vectors for tidal cycle 4.



Vector No.	Date	Time
1	17 Dec 75	1610
2		1710
3		1810
4		1910
5		2010
6		2110
7		2210
8		2310
9	18 Dec 75	0010
10		0110
11		0210
12		0310

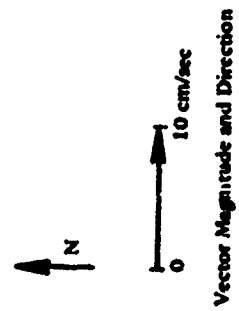
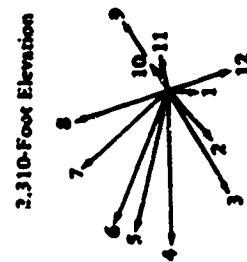
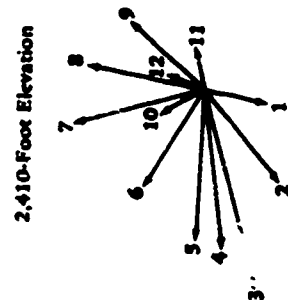
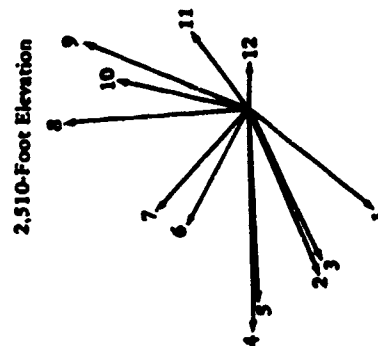
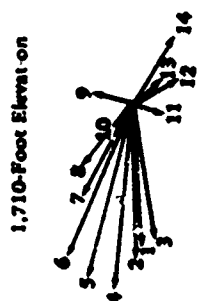
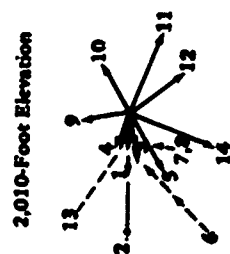
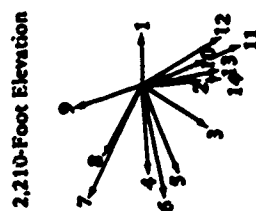


Figure 6-10. Current vectors for tidal cycle 5.



Vector No.	Date	Time
1	18 Dec 75	0310
2		0410
3		0510
4		0610
5		0710
6		0810
7		0910
8		1010
9		1110
10		1210
11		1310
12		1410
13		1510
14		1610

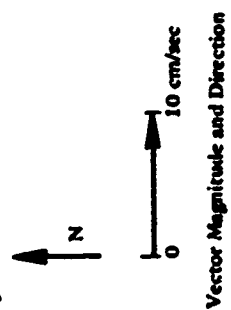
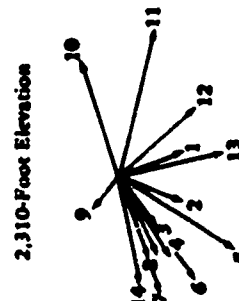
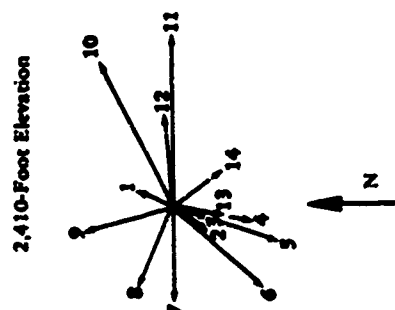
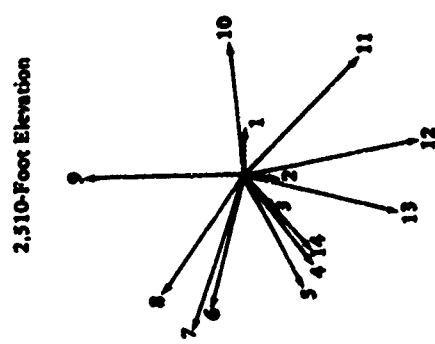


Figure 6-11. Current vectors for tidal cycle 6.

910-Foot Elevation



1,710-Foot Elevation



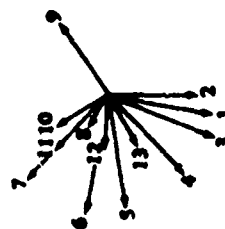
2,010-Foot Elevation



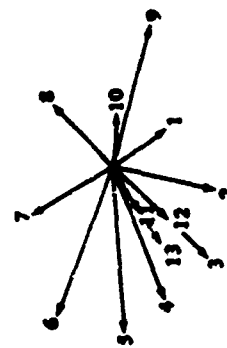
2,210-Foot Elevation



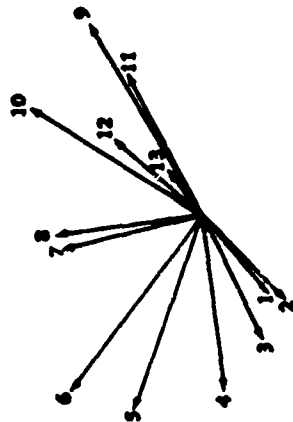
2,310-Foot Elevation



2,410-Foot Elevation



2,510-Foot Elevation



Vector No.	Date	Time
1	18 Dec 75	1610
2		1710
3		1810
4		1910
5		2010
6		2110
7		2210
8		2310
9	19 Dec 75	0010
10		0110
11		0210
12		0310
13		0410



0 10 cm/sec

Vector Magnitude and Direction

Figure 6-12. Current vectors for tidal cycle 7.

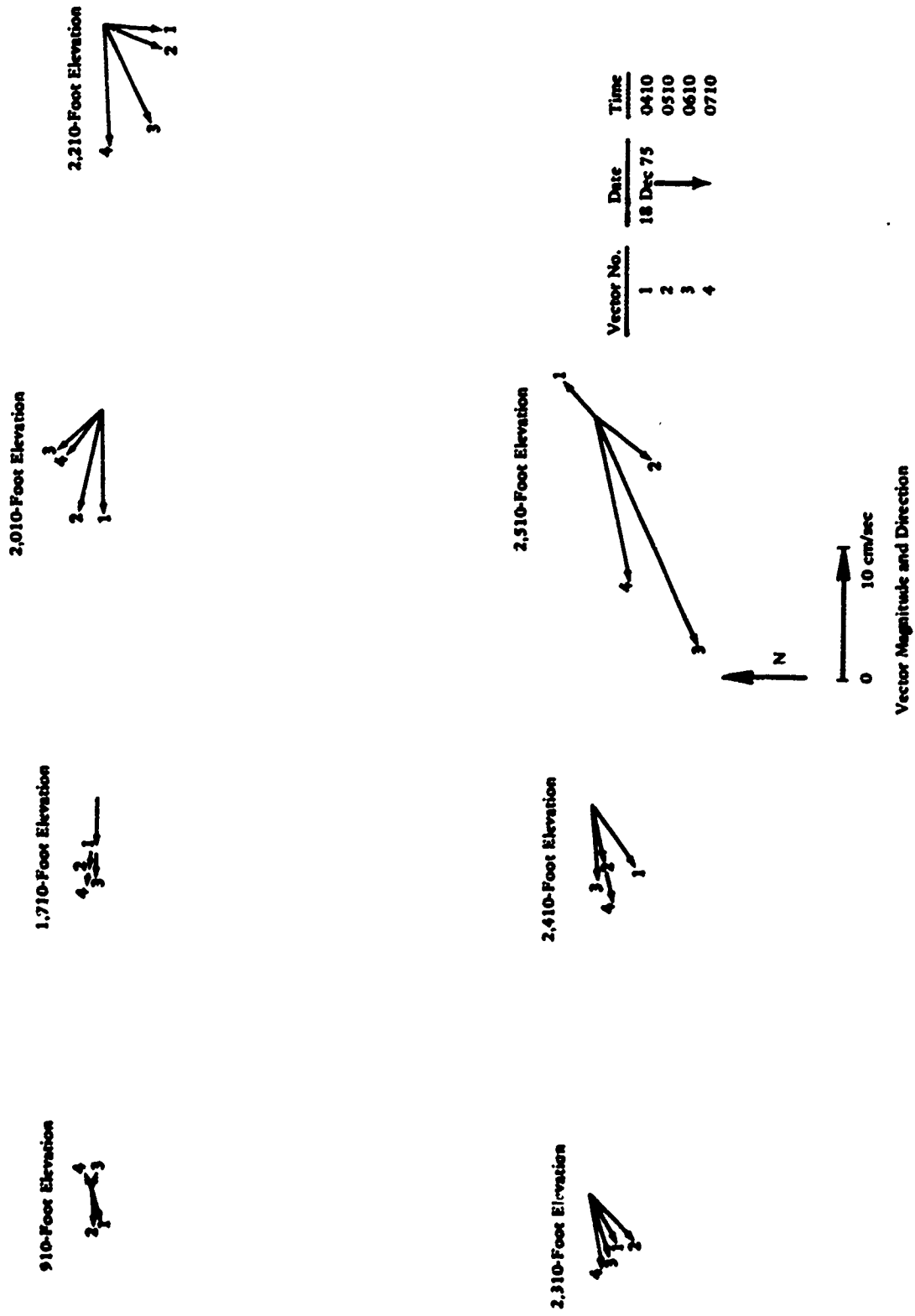


Figure 6-13. Current vectors for tidal cycle 8.

During tidal cycles 3, 4, and 8, strong shear layers were present near the top of the structure. For tidal cycle 3, two shear conditions actually exist: one between the meters at the 2,010- and 2,210-foot elevations, and a second, more important one between the meters at the 2,310- and 2,410-foot elevations. For tidal cycles 4 and 8, the shear appears between the meters at the 2,410- and 2,510-foot elevations. The current meters provide discrete information about the current regime at the various elevations, but do not provide insight into the nature of the shear layers between meters, i.e., their thickness, the elevations where they begin or end, or the absolute magnitude of the shear current at elevations away from the current meters. Since the computer program DESADE uses linear interpolation to construct the current profile between adjacent current meters, shear layers, when present, will tend to increase the differences between measured and predicted results. This difference is maximized when the shear occurs near the top of the structure (the 2,310-, 2,410-, and 2,510-foot elevations) as the currents generally become higher as the elevation increases. The buoys and delta cables produce a large percentage of drag force on the structure which will be in error if the linear interpolation procedure does not correctly depict the current regime. Also, the structure acts much like a cantilever beam; a unit of force or error in force produces the greatest structure change or predicted change error when applied at the top of the structure.

When the shear layers occur well below the top of the structure, as they do in tidal cycles 1 and 5, the effects of errors in depicting the current regime, while important, are not as devastating as when they occur near the top.

When strong shear layers are absent, as they appear to be during cycles 2, 6, and 7, the predictive capabilities of the computer program are maximized. Figure 6-14 shows the measured and predicted response of all operational acoustic nodes during tidal cycle 1. The current regime, as indicated by the current meter data on Figure 6-6, has a significant shear between the 1,710- and 2,010-foot elevations during the entire cycle. In addition, a shear begins to develop in the 2,310-, 2,410-, 2,510-foot elevation region during the last 2 hours of the cycle. The differences between the measured and predicted results at the nodes are most pronounced during the

early portion of the cycle when the current velocity is increasing from a few cm/sec to 18 cm/sec. The average difference between results for this period is approximately 5 feet with a maximum difference of nearly 8 feet occurring at node E.

Figure 6-15 is a large-scale plot of the response of node B to tidal cycle 1. Note that this figure, as well as all subsequent figures for node B, has the time of day shown at various datum points. The times allow the reader to more clearly discern the differences and similarities between the measured and predicted results. The times shown on the displacement curves can be used in conjunction with the times given with the current vector figures to get a feel for the current conditions at the time the data were taken.

Figure 6-16 shows the measured and predicted response of node B during tidal cycle 2. Overall, the match between the results is quite good with differences averaging approximately 2 feet. If the bias is removed by shifting the predicted data 2 feet in the positive-x and 2 feet in the positive-y directions, then an excellent reproduction of the measured data can be produced. Note that even the micro details within the tidal cycle that occur near 2320 hours can be easily discerned. As the reader will recall, the current data for this cycle, shown on Figure 6-7, does not have strong shear conditions present. On Figure 6-17, the measured and shifted predicted data are shown along with a prediction curve for a 1.55 drag coefficient, the measured value for the nonstrumming SEACON II cable. The differences between these two prediction curves are the result of analytical approximations for the effects of cable strumming of the delta cable.

Figures 6-18 and 6-19 show the measured and predicted results for tidal cycles 3 and 4, respectively. During both of these cycles, strong shear layers were present at elevations near that of the delta. For cycle 3, the measured response of the structures is less than the predicted results, while the overall shape of the response curves are similar. For cycle 4, the predicted curve is much less than the measured curve, and the two curves do not have similar shapes.

Close inspection of the current vector plot of tidal cycle 3 (Figure 6-8) shows that the major current discontinuity or shear occurs at the 2,310-foot elevation, which is slightly below the delta. The interpolation of current data by the computer program must generate more drag force than is actually present.

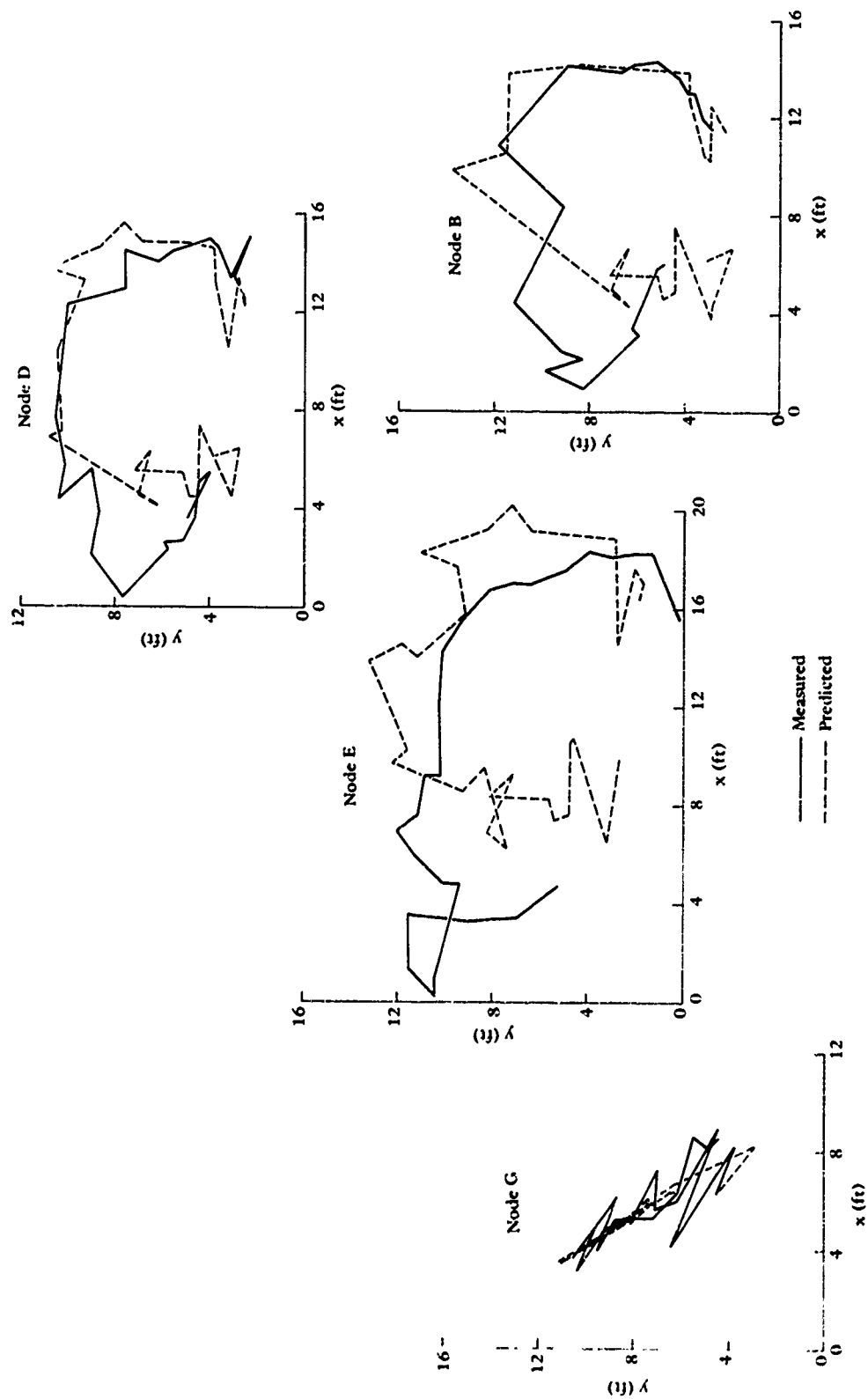


Figure 6-14. Displacement of nodes B, D, E, and G during tidal cycle 1.

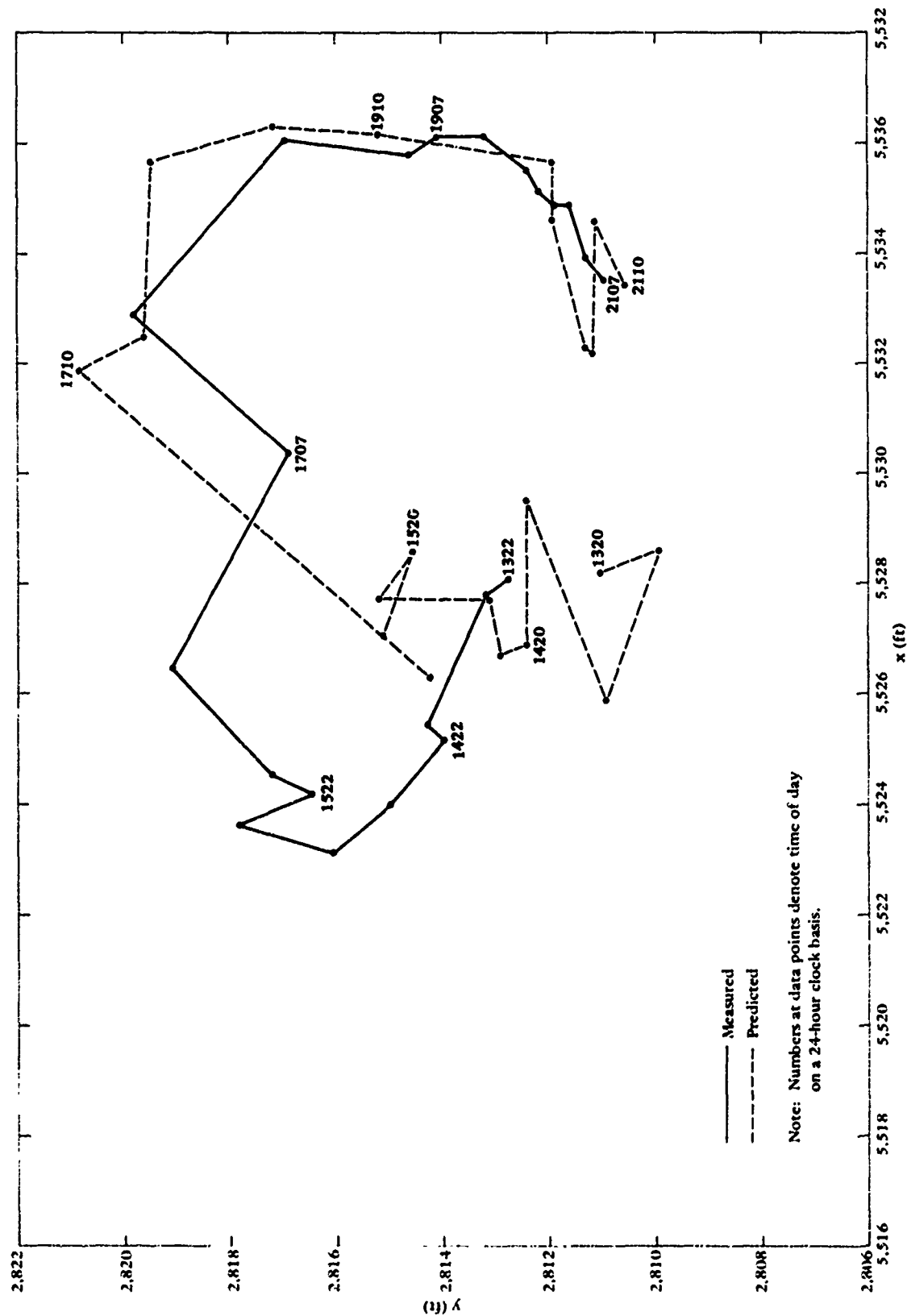


Figure 6-15. Displacement of node B during tidal cycle 1.





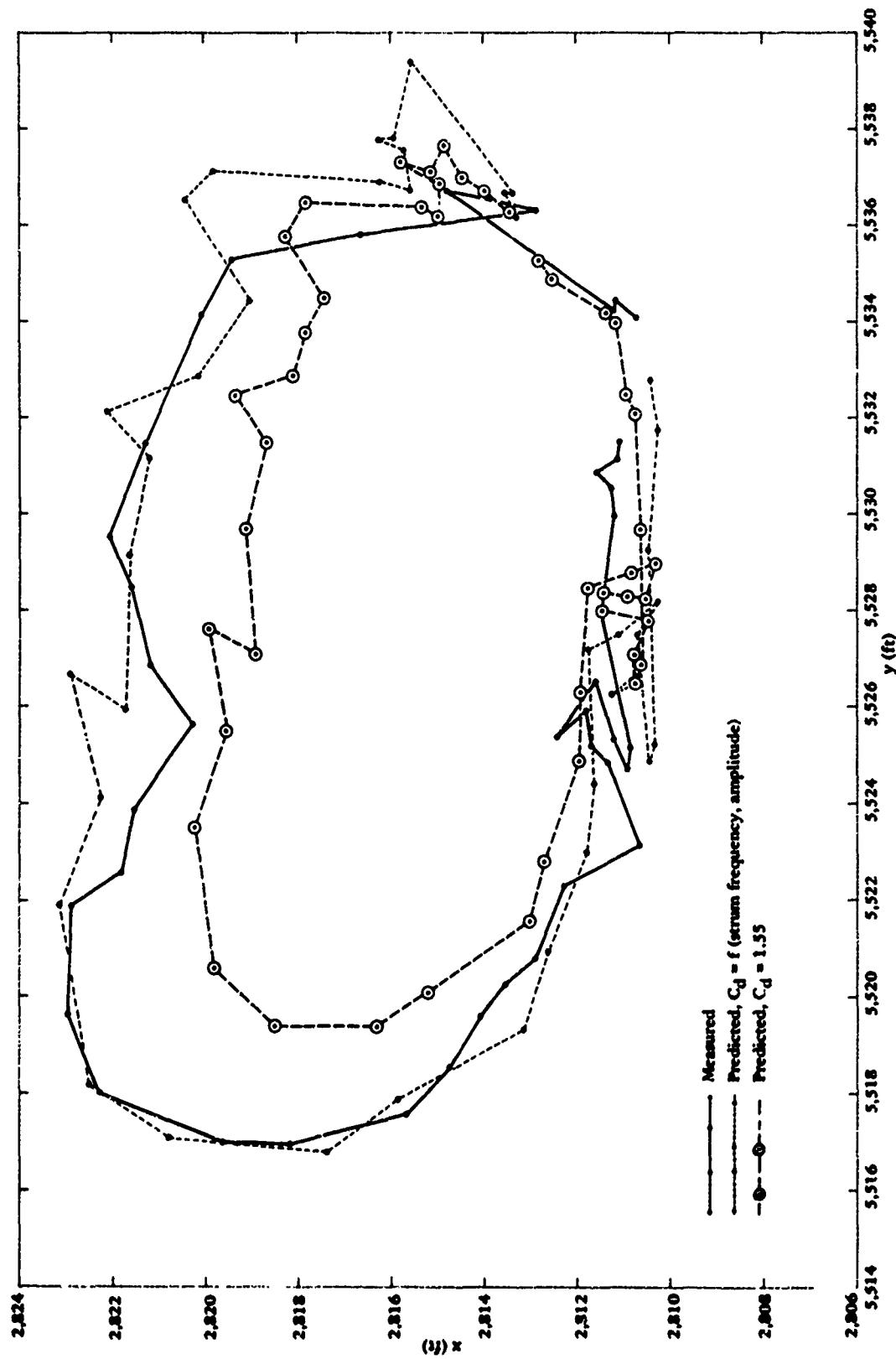


Figure 6-17. Displacement of node B during tidal cycle 2 using adjusted drag coefficients.

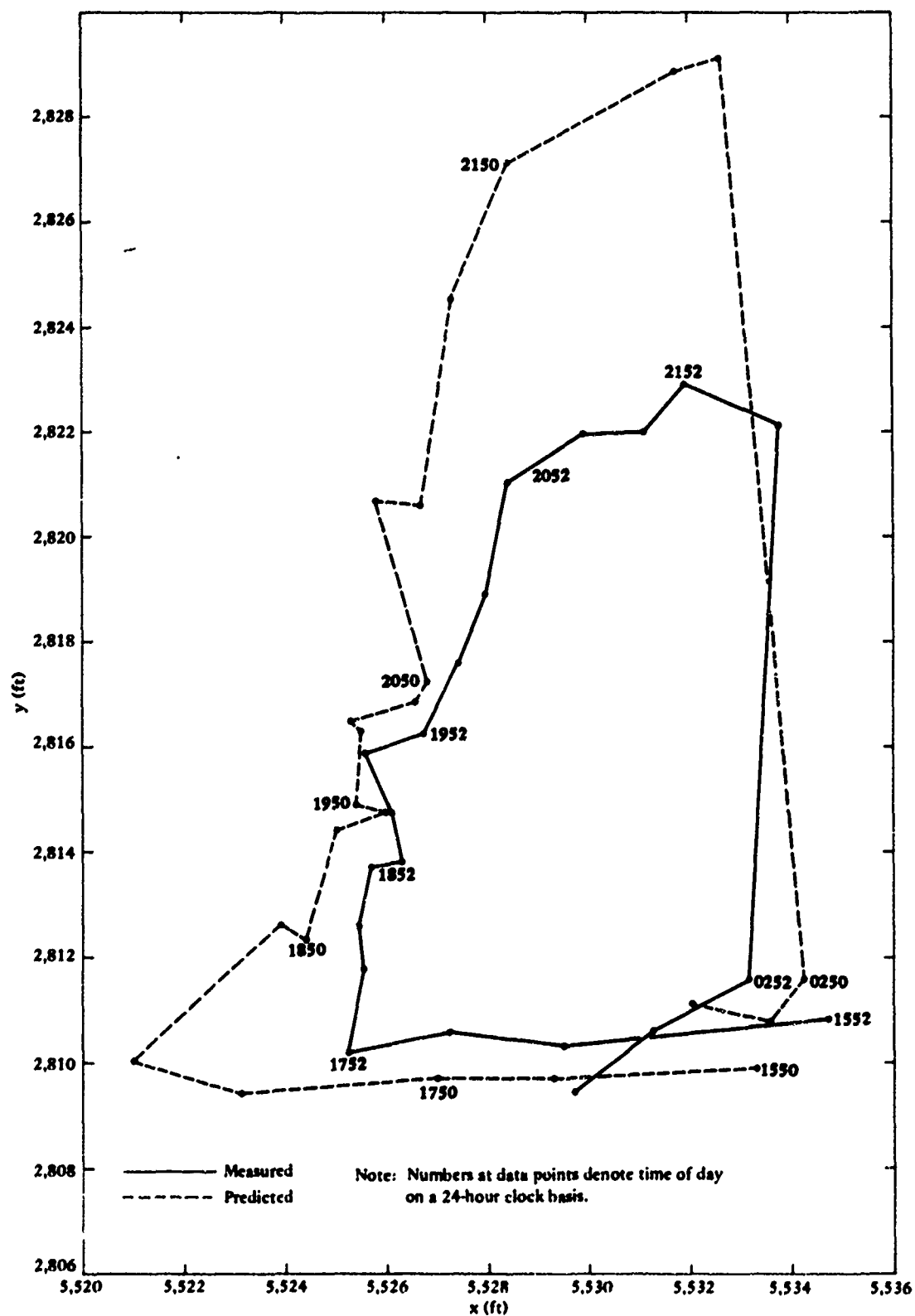


Figure 6-18. Displacement of node B during tidal cycle 3.

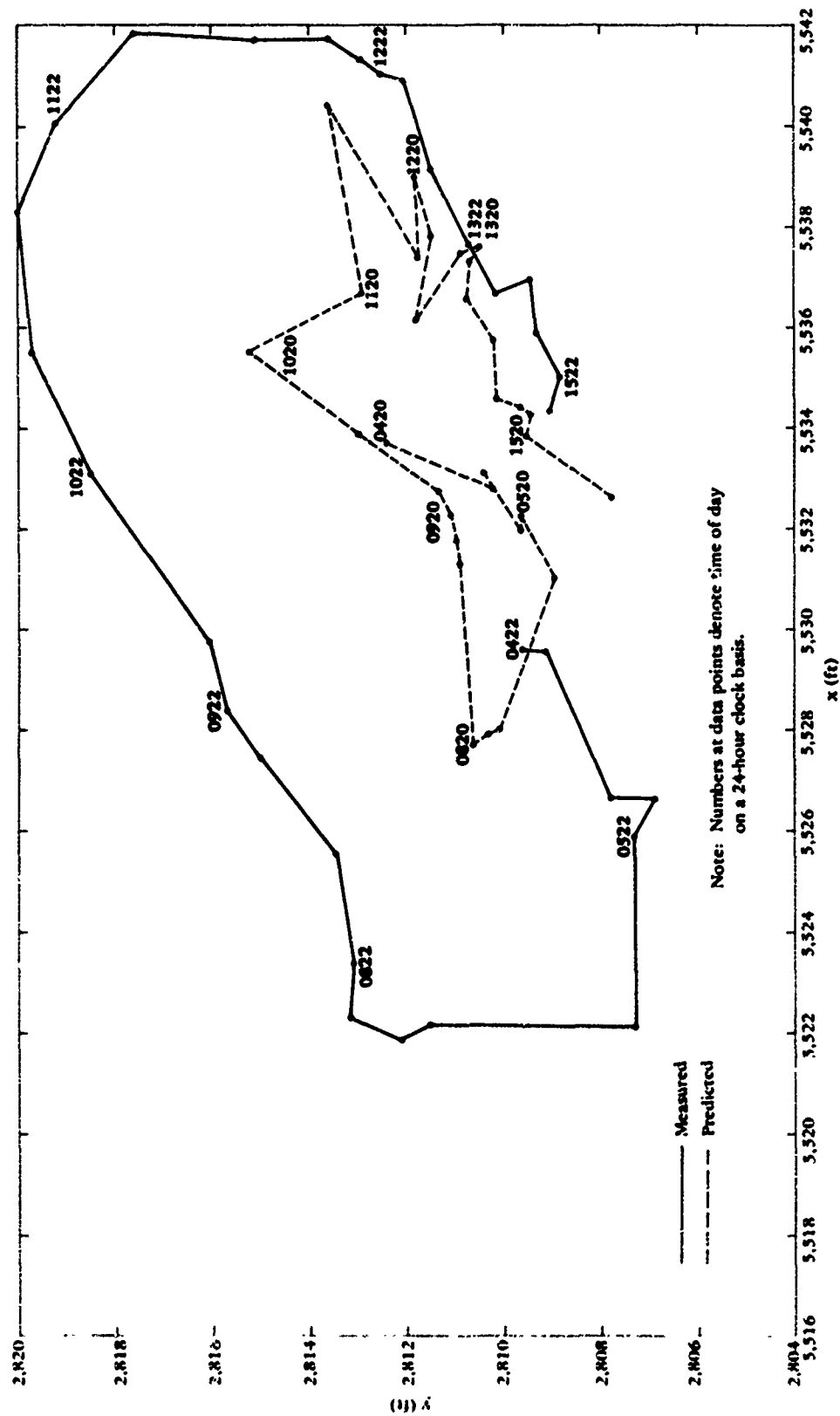


Figure 6-19. Displacement of node B during tidal cycle 4.

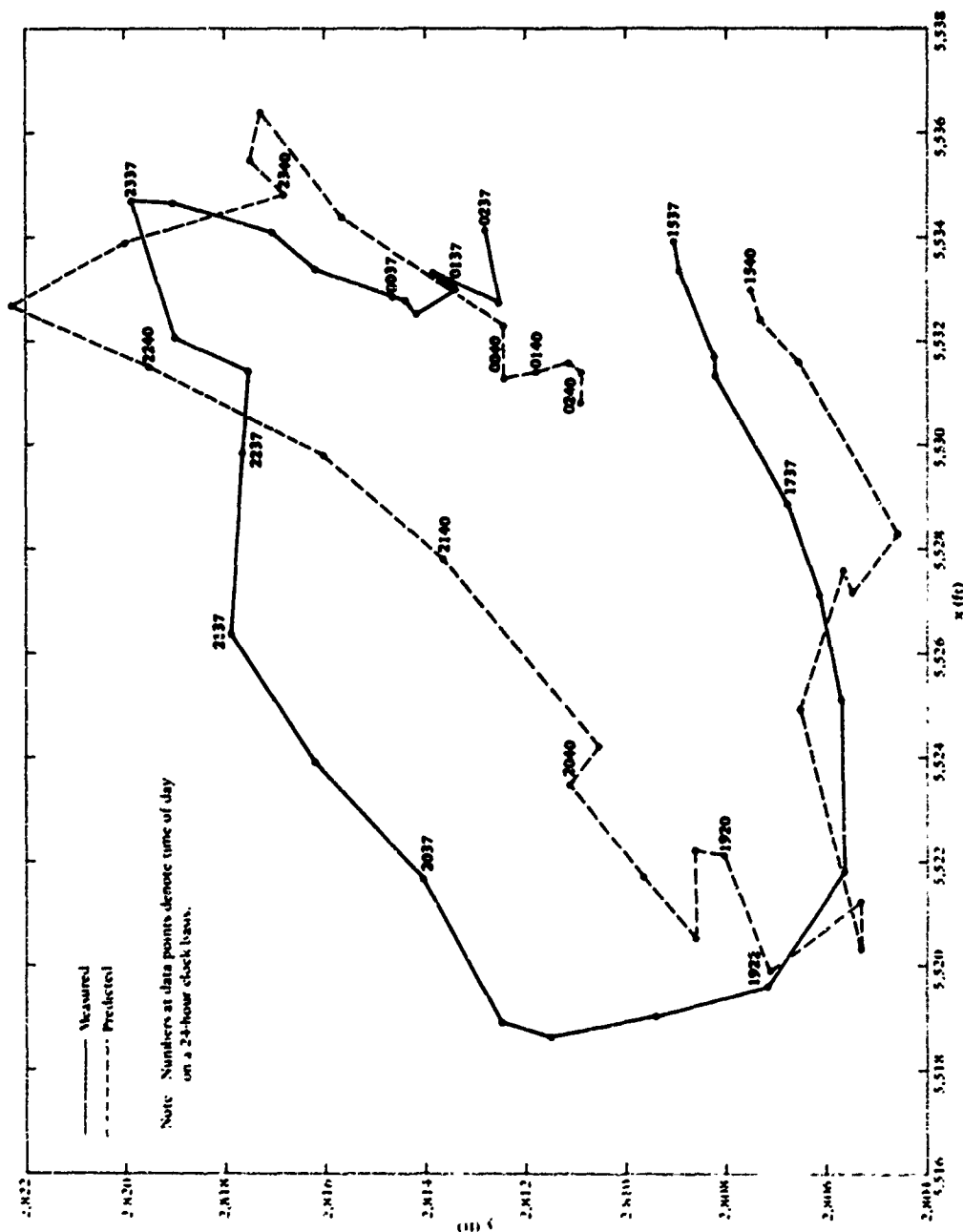


Figure 6-20. Displacement of node B during tidal cycle 5.

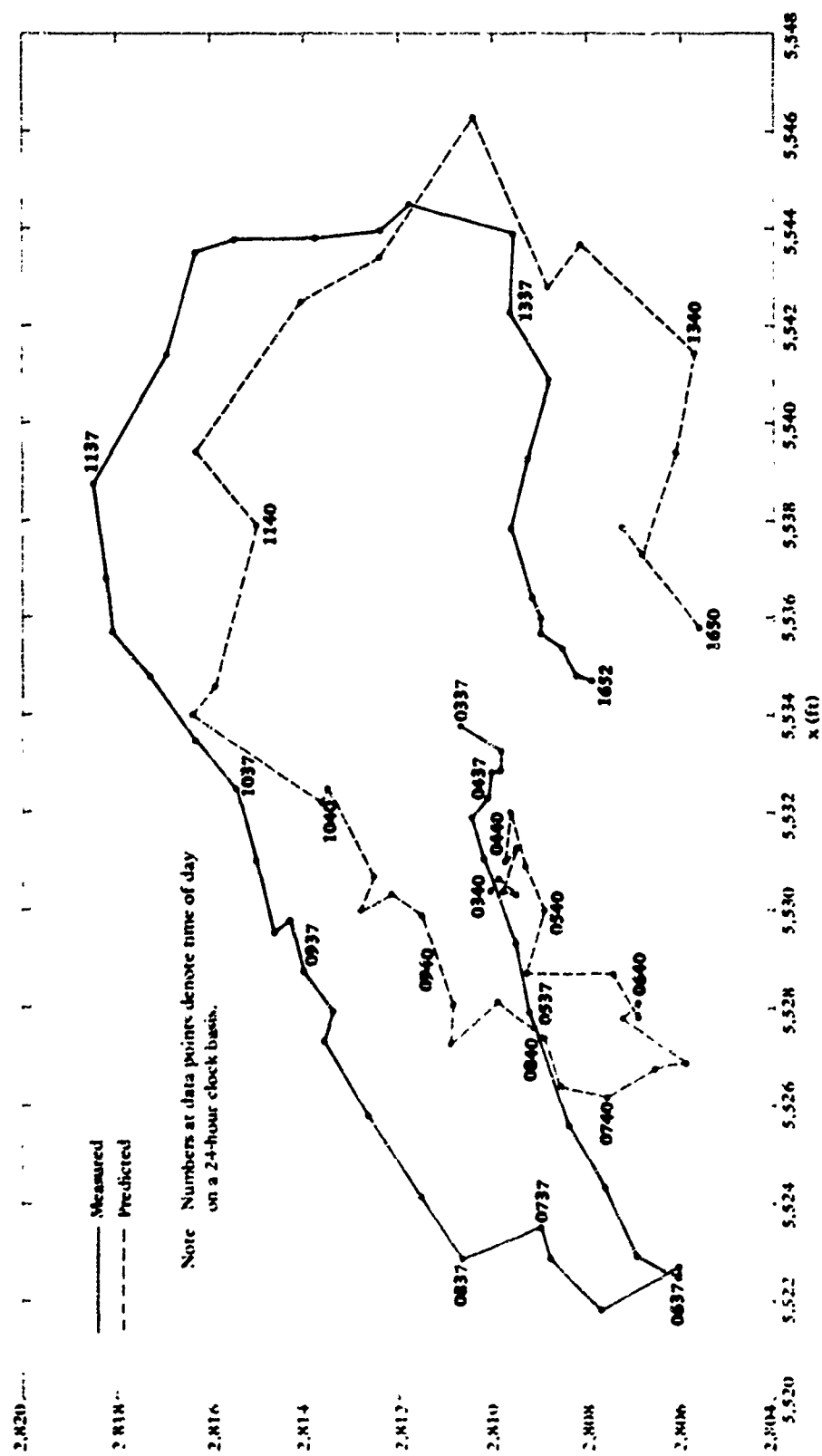


Figure 6-21. Displacement of node B during tidal cycle 6.

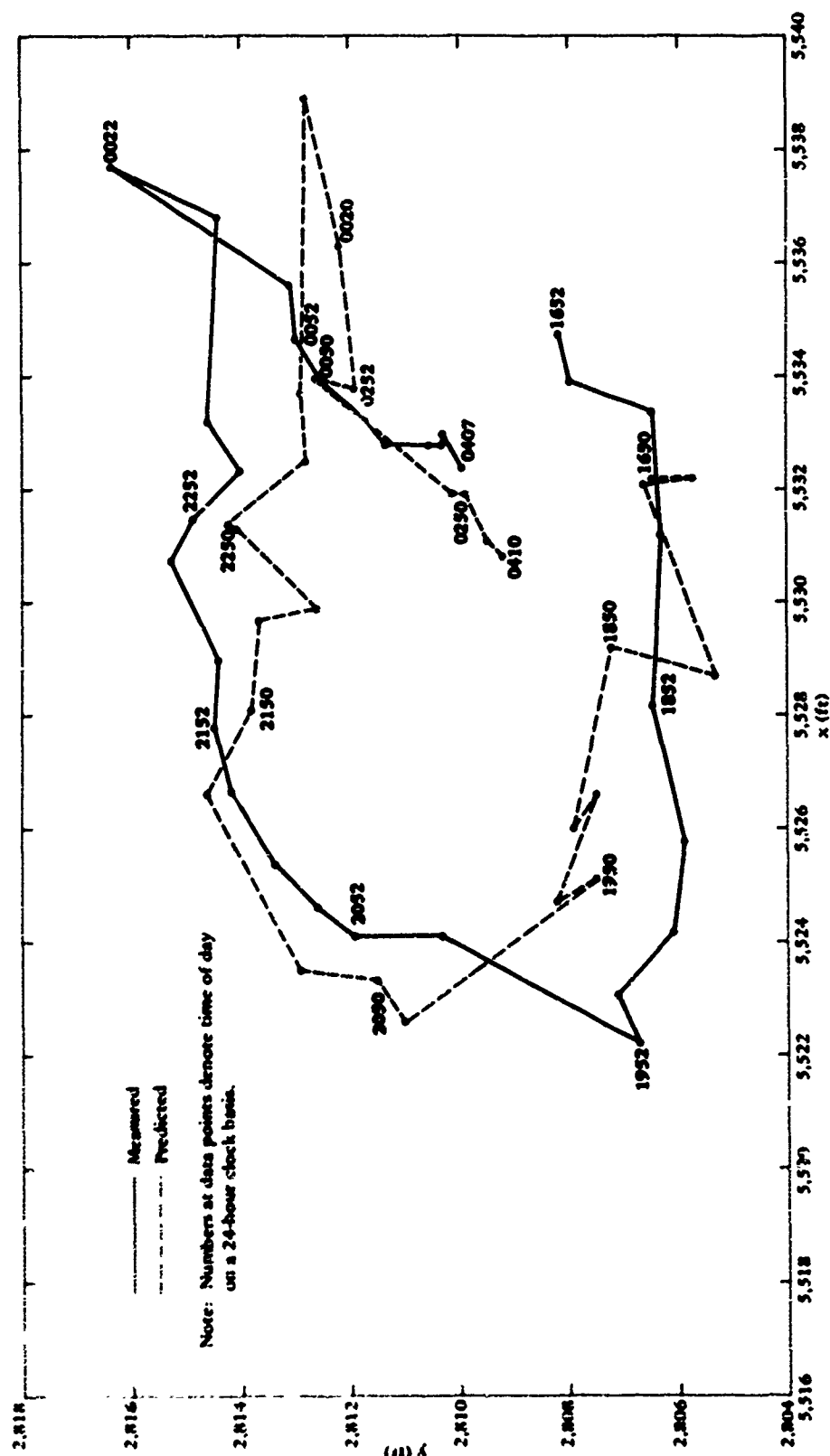


Figure 6-22. Displacement of node B during tidal cycle 7.

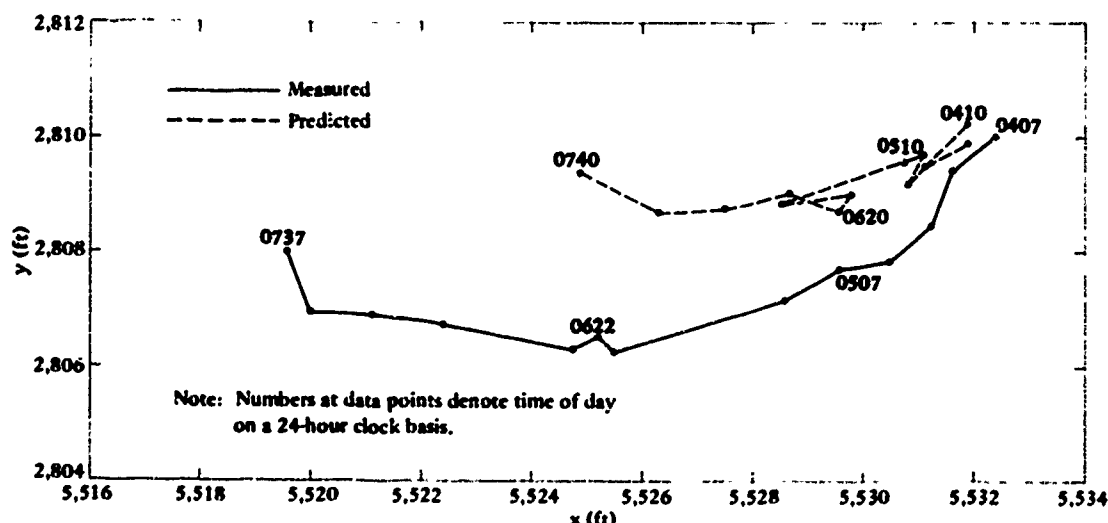


Figure 6-23. Displacement of node B during tidal cycle 8.

Inspection of Figure 6-9, the current vector plots for tidal cycle 4, shows that a major discontinuity occurs between the 2,310- and 2,410-foot elevations during the first half of the cycle and between the 2,410- and 2,510-foot elevations during the entire cycle. It is apparent from inspection of the response curves that the current data have not been properly modeled. This is not the fault of the program; rather, it is due to a lack of understanding of the nature of the shears. The discrete data collected by the current meters are used to construct a current profile by linear interpolation of the current data. It is clear that when shear conditions are present, the linear interpolation of the data does not result in a valid depiction of the actual current profile, and, thus, the program does not produce a valid depiction of the structure's response.

Figures 6-20 through 6-23 show the response of the structure during tidal cycles 5 through 8, respectively. The quality of the match between the measured and predicted results is strongly related to the presence or absence of shears in the current data. In general terms, when shears are present, the match between measured and predicted results is of poor quality. When the shear is absent, the match improves.

## SUMMARY

To summarize the Results section, the SEACON II data have shown three important results. First, cable drag coefficients need to be precisely determined. This procedure should include tests of non-strumming cables, analyses to determine the propensity of the cable to strum, and application of appropriate drag coefficient amplification factors to account for the increased drag if strumming is predicted. Second, to precisely predict the response of cable structures in the ocean, it is necessary to precisely depict the current conditions. This means data must be collected from very closely spaced current sensors, or the oceanic processes that create and control shear conditions must be better understood. In this way, current profiles that truly represent the actual conditions can be constructed. Third, the DESADE program provides excellent predictions of the response of complex structures in the ocean when correct drag coefficient data are used and the current regime is without major shear layers.

These conclusions are based on the examination of eight tidal cycles spanning a period of approximately 8 days. These conclusions will be confirmed by examining additional data taken during the



SEACON II experiment for periods when the current velocity exceeded 20 cm/sec and shear phenomenon was not strongly present. In addition, the DESADE program will be modified to allow known tangential drag effects to be included.

#### **SECTION 4 - CONCLUSIONS AND RECOMMENDATIONS**

1. The computer program DESADE appears to be capable of predicting the steady-state response of complex, submerged cable systems if the drag coefficient for the cables and the current regime are properly modeled.
2. A procedure for modal analysis/drag coefficient amplification factor should be incorporated into DESADE so that cable strumming effects can automatically be assessed.
3. A standard test procedure should be developed that provides consistent and precise values for the nonstrumming cable drag coefficients used in DESADE and other programs.

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## Appendix A

### ANALYSIS OF CORROSION OF SEACON II STRUCTURE

By James F. Jenkins

This analysis of the corrosion of the SEACON II structure is based primarily upon visual observations of the structure made during its recovery on 12 May 1976. The analysis is presented in the order of item inspection, which roughly follows the order of item retrieval. The observations were made within one half hour or less of the recovery of the item, unless otherwise noted.

#### VISUAL OBSERVATIONS

##### Crown Buoy

As shown in Figure A-1 the crown buoy was covered with a heavy accumulation of marine fouling organisms, but there was no blistering or peeling of the paint coating. There was no rust where the paint had been mechanically damaged. The zinc anodes of the cathodic protection system were nearly completely consumed as shown in Figure A-2. These anodes and others on the array consisted of a 1-1/4 x 3/16 x 16-inch mild steel strap around which was cast approximately 10 pounds of anode quality zinc conforming to MIL-A-18001G. The steel strap projected approximately 2 inches from either end of the anode and was used to attach the anode to the structure being protected. In some cases, such as on the crown buoy, the anodes were sawn in half because a number of smaller anodes were required to achieve cathodic coverage. Figure A-2 shows the steel strap with only a very small amount of zinc remaining. As the cathodic protection system on the entire array was designed for a 2-year life, it is evident that the design criteria were appropriate for the protection of painted steel in shallow water.

##### Crown Wire

The jacket had been stripped from the 1-inch-diameter 3x24 construction galvanized steel

electromechanical crown cable for approximately 25 feet just below the crown buoy during the recovery procedure. The exposed strength wires had a dull grey surface, but no rust. As the crown cable was being retrieved, a number of patches of marine growth were noted on the wire jacket that had been exposed at depths greater than 200 feet and more than 50 feet above the bottom. A typical patch of growth on the crown cable is shown in Figure A-3.

##### Crown Line Instrument Canister

As the crown line instrument canister was retrieved, a gas-charged white slurry was discharged from the lower end of the cable breakout (Figure A-4). As shown in Figure A-5, the hydrophone and bracket had separated from the main canister. Some portions of the bolts used to attach the hydrophone case to the canister were still present. They were not severely corroded, but had been fractured. Since the fractured surfaces were rusted, it is obvious the bolts failed due to overload a considerable time prior to recovery. The zinc anode on the hydrophone was approximately three-quarters consumed. Some portions of the hydrophone assembly had been electrically isolated from the anode and were corroded. However, no corrosion failures had occurred.

##### Clump Anchor

From the discoloration of the surface of the clump anchor, as shown in Figure A-6, it was evident that bottom sediments had piled up on one side of the clump anchor as it was dragged forward during implant. There was no rust evident on the external surfaces of the clump anchor. As shown in Figure A-7, there was some blistering of the white top coat on the clump anchor. Figure A-7 also shows the zinc anodes on the clump anchor to be essentially unconsumed. These full-size 11-pound zinc anodes

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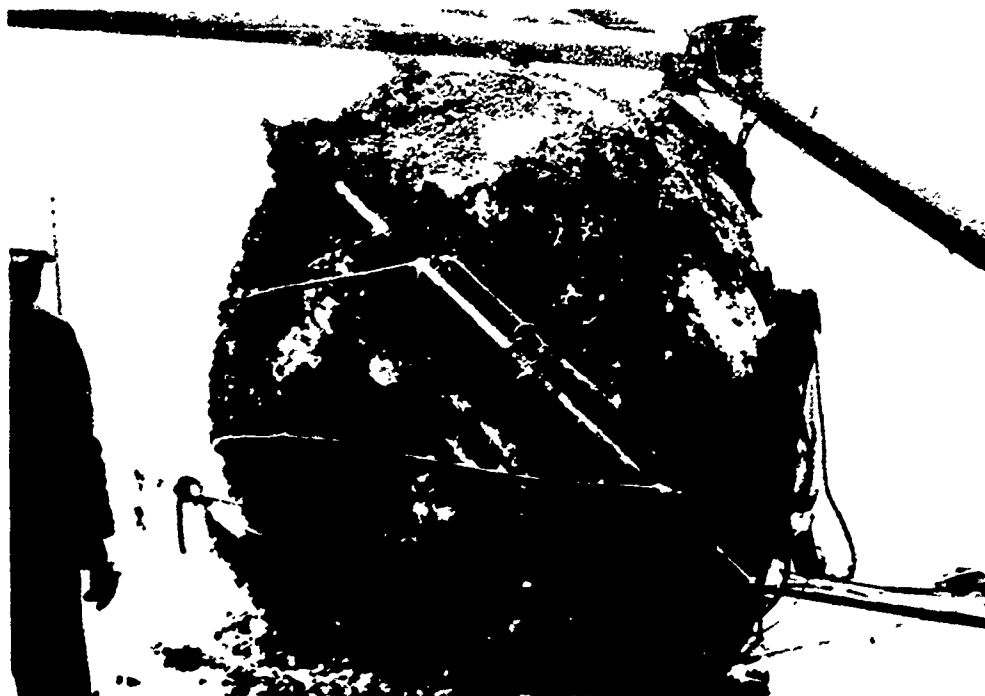


Figure A-1. Crown buoy with heavy marine fouling.



Figure A-2. Nearly consumed zinc anode on crown buoy.

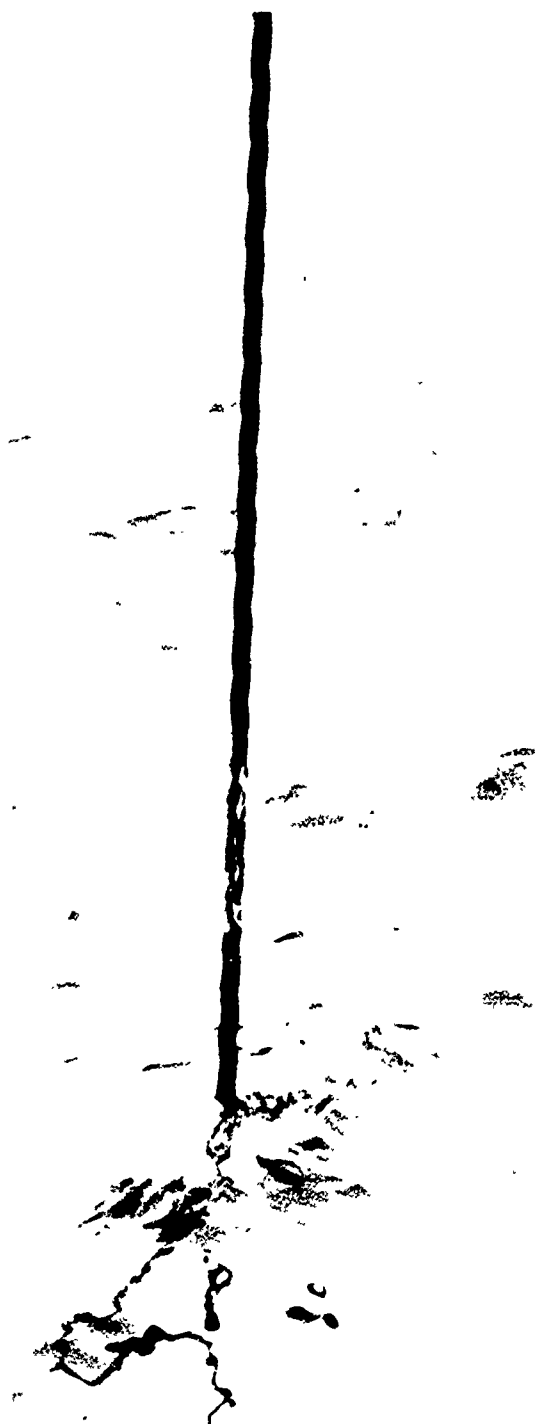


Figure A-3. Typical patch of marine growth on crown line.

were designed to have a 3-year life. A closer inspection of these anodes showed that they had been partially consumed, but that the products resulting from the corrosion of the anodes had retained the size and shape of the original anode. When, as shown in Figure A-8, the loose coating was removed, the anodes were found to be approximately one-third consumed. This rate of consumption was somewhat lower than expected, which indicates the design parameters derived from near-surface experience are not directly applicable to deep water, at least in this location. The external hardware on the clump anchor that was electrically bonded to the cathodic protection system was uncorroded. The hardware that was not electrically bonded to the cathodic protection system, such as the connection to the node buoy cable, was corroded but not severely deteriorated, particularly when it had been hot-dip galvanized prior to exposure. The portions of the system that were inside the clump anchor were not inspected in detail, because the anchor could not be drained at this stage of recovery. However, the inside was covered with black slime that had the odor of hydrogen sulfide (rotten eggs). There was considerable rusting of some interior components of the clump anchor.

#### Leg L3

Leg L3, which consisted of 1/2-inch-diameter 3x19 construction galvanized and jacketed steel electromechanical cable, connected the clump anchor to node buoy 3. The jacketing on the leg was unbroken. As shown in Figure A-9, there were several areas where marine organisms were attached to the jacketing.

#### Leg L3 Instrument Canister

Several portions of the instrument canister on leg L3 showed considerable corrosion, they were the fasteners on the PVC swivel assembly, the hydrophone cage bolts, and the stainless steel hydrophone boot clamp. These items were not electrically bonded to the zinc anode cathodic protection system. The portions of the assembly that were electrically bonded to the cathodic protection system were not corroded. The two small (1-pound) steel cone zinc disc anodes were approximately one-half consumed.



Figure A-4. Gas-charged white slurry discharged from hole in crown line cable pocket.



Figure A-5. Hydrophone and its case separated from crown line instrument station canister.

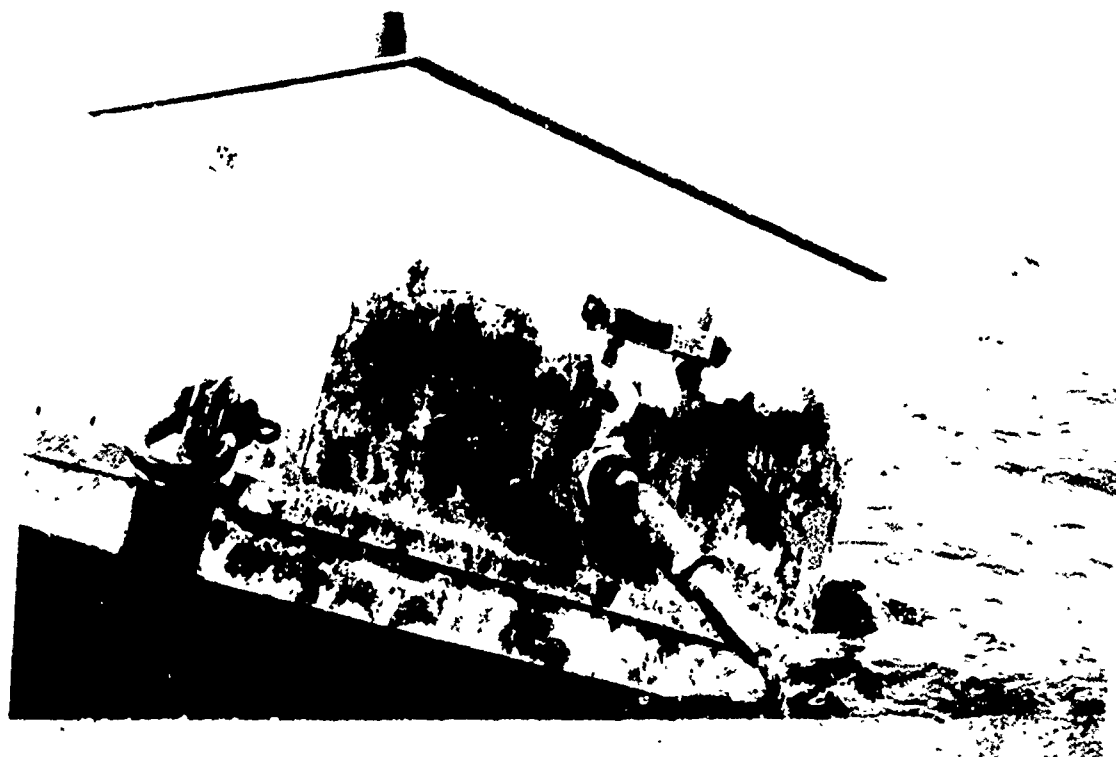


Figure A-6. Recovered clump anchor. Mudline shows where bottom material piled up in front of anchor.

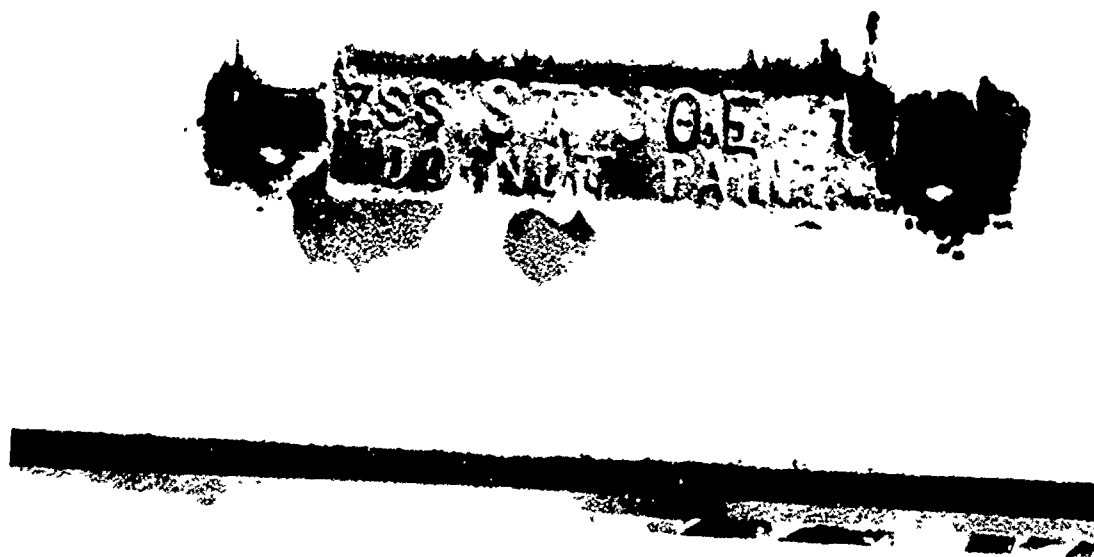


Figure A 7. Clump anchor showing blistering of white topcoat and apparently unconsumed zinc anode



Figure A-8. Corrosion products on clump anchor zinc anode scraped away to show amount of anode consumed.



Figure A-9. Leg 1.3 with marine organisms attached.



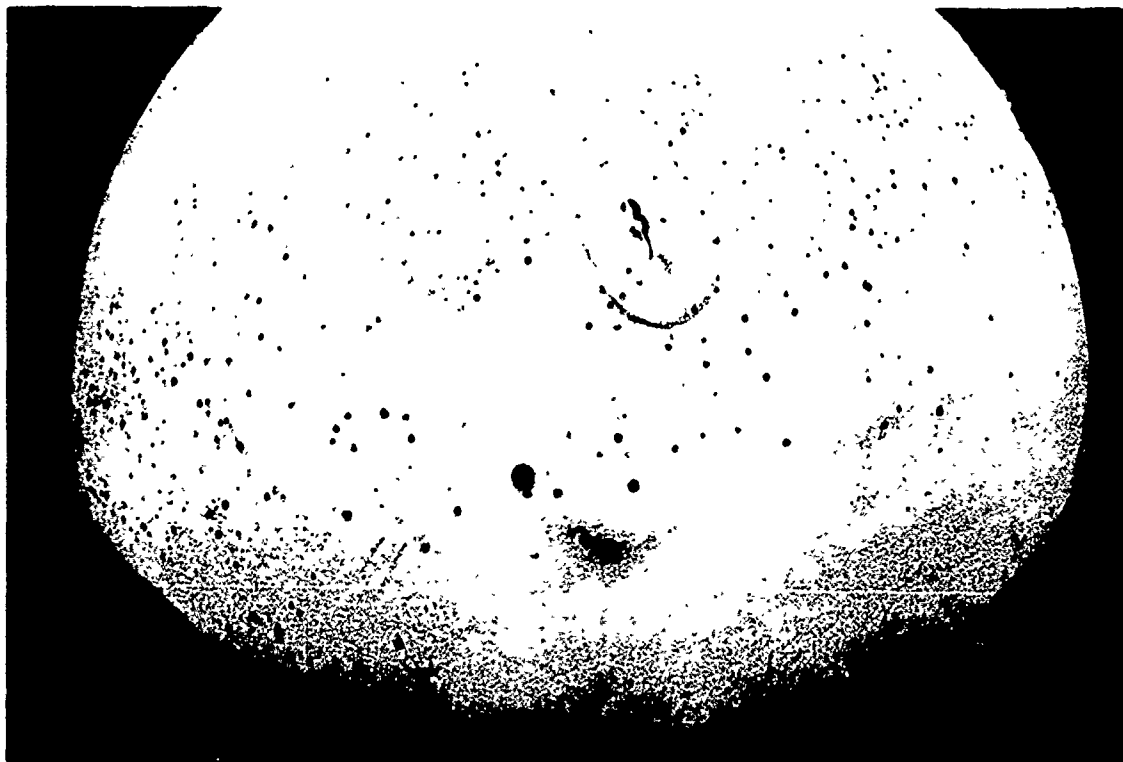


Figure A-10. Node buoy 3 with light marine fouling and blistered outer paint coating.

### Node Buoy 3

As shown in Figure A-10, there were some marine organisms, urchins, and scallops on this buoy. The top coat of paint was blistered, but the underlying primer coat was not. The zinc anodes near the upper bail on the buoy were approximately one-half consumed. The termination canister at the base of the buoy was hot-dip galvanized and had a dark gray surface. The anodes on this canister were approximately one-quarter consumed. The electromechanical cable ball joints and terminations connected to the canister evidently were not well-bonded electrically to the canister and, therefore, were rusted. This corrosion was not severe, and it is possible that the terminations received partial or intermittent protection. The hydrophone cage attachment, which was electrically isolated from the cathodic protection system, showed some superficial corrosion. The stainless steel hydrophone boot band showed evidence of crevice corrosion at the band buckle, but it had not failed.

### Delta Arm Cables

The delta arm cables between the three node buoys were 1/2-inch-diameter 3x19 construction galvanized and jacketed steel electromechanical cable. The jacketing on the cables was intact, and, as shown in Figure A-11, there were also patches of fouling organisms.

### Delta Instrument Canisters

The instrument canisters located on the delta arms between node buoys 1 and 3 and 2 and 3 were similar in construction and condition to the canister on mooring leg 1.3.

### Accelerometer and Tensiometer

The accelerometer and tensiometer in the delta arm between node buoys 1 and 2 were attached to the delta arm cable with a preformed spiral grip



Figure A-11. Marine fouling on one of the delta cables.

fabricated from galvanized steel. As with other similar terminations, these terminations were covered with patches of white corrosion products. However, no rust was found on these or other similar terminations.

#### Node Buoys 1 and 2

These node buoys, the attached hardware, and the cathodic protection system were essentially identical to node buoy 3 in construction and condition. When the condition of the nine ball joints and cable terminations at these three buoys was compared, a wide variation in the amount of corrosion was noted. This variation in performance confirms the fact that there was only partial or intermittent bonding of the terminations to the buoy cathodic protection system.

#### Anchor Legs

Anchor leg 1.2 from node buoy 2 to its embedment anchor was parted in an attempt to retrieve the

anchor. The 1/2-inch-diameter 3x19 construction galvanized and jacketed steel wire rope was undamaged and had a few patches of fouling organisms on the surface of the jacket similar to those found on the other cables in the array. The bitter end of the failed cable showed bright cup and cone and shear failures, indicating that it failed due to overload. The surfaces of the exposed wires were a uniform dark gray with no evidence of rusting.

Anchor leg 1.1 from node buoy 1 to its embedment anchor was retrieved without parting. The jacket had been stripped from the wire over a considerable portion of its length. The wire had a uniform dark gray color and exhibited no rusting.

#### Embedment Anchor A1

Embedment anchor A1 was connected to the leg wire with unjacketed steel wire rope. The embedment anchor launch vehicle was retrieved with the anchor. While this was not planned, it was fortunate because there was evidence that the launch vehicle had been

partially embedded in the bottom sediments. This information can be used to place an upper limit on the tension in this leg. The unjacketed wire rope used to connect the anchor fluke to the structure leg was not significantly deteriorated. However, the presence of scattered rust spots, such as those shown in Figure A-12 where the wire had been at least partially exposed to the seawater above the bottom sediments, could be used to determine the approximate embedment depth of the anchor fluke. This depth was approximately 20 feet. The anchor fluke and steel portions of the launch vehicle were not significantly deteriorated. The aluminum safe-and-arm canister on the launch vehicle was corroded, but it was lost before a detailed examination could be made. The interior of the safe-and-arm device was uncorroded. This indicates that the canister was not flooded prior to recovery.

#### **Construction Mooring Buoy**

The 9-1/2-foot-diameter steel construction mooring surface buoy was heavily encrusted with fouling organisms. The buoy and attached hardware showed deterioration typical of that experienced on similar equipment exposed for similar times in this area. No structural failures had occurred due to corrosion.

#### **Construction Mooring Line**

The construction mooring line was 3/4-inch-diameter 3x19 construction galvanized and jacketed steel wire rope. This line was undamaged and, unlike the other jacketed lines in the structure, did not have any significant amounts of fouling attached to its surface.

#### **Embedment Anchor for Mooring Buoy**

The embedment anchor for the mooring buoy was of the same construction and the same condition as embedment anchor A1. The launch vehicle was not recovered with this anchor.



Figure A-12. Scattered rust spots on down-haul cable, indicates portion of cable in water column.

## LABORATORY ANALYSIS

The only portions of the SEACON II structure that were subjected to laboratory analysis to evaluate corrosion were those sections of the projector cables which were recovered prior to the recovery of the major portions of the structure.

These 3/16-inch double-armored electro-mechanical cables were severely deteriorated and had parted due to corrosion. Examination of the bitter ends of both cables showed that there were many armor wires that had failed due to corrosion. Starting 2 inches from the bitter end, the corroded wires were tapered from nearly their original size to a thin point at the bitter end. Away from the bitter end of the cable the wires showed some rust, but were not significantly thinned. There were several portions of the retrieval projector cables that showed corroded areas similar to those found on the bitter end of the cables. Electrical tests made after the cables were disassembled showed insulation faults in the conductor wires adjacent to the areas of accelerated armor wire corrosion. Even small current leakage from these faults can account for and is probably the cause of the projector cable failure.

## CONCLUSIONS

1. The present criteria can be used for designing an ocean cable structure with a minimum 2-year life.
2. The present design criteria do not give precise prediction of the behavior of sacrificial anode systems. Thus, optimum designs cannot be made.
3. Electrical faults can cause rapid deterioration of cable structures.

## Appendix B

### UNDERWATER TENSION LOAD CELL

The underwater tension load cell, which is fabricated from components (see Figure B-1), has a failsafe collar and a replaceable tension link, utilizes an oil-filled pressure-balanced system, has the capability of adapting to a cable termination, and allows all electrical conductors to pass uninterrupted through the load cell. The assembly of the tension load cell is as follows (see Figure B-1):

<u>Items</u>	<u>Description</u>
1, 2	End terminations; can be machined to fit any cable termination.
3	Failsafe collar; is installed around the unit. If the tension link breaks, the load is taken up at the load bolts (Item 7).
4	Tension link itself; a hollow tube with strain gage instrumentation on the outer surface. The link is attached to each of the end fittings (Items 1 and 2) with bolts (Item 14). The electrical conductors pass through the end fitting (Item 2), into an end plug (Item 6), through Item 6, and through a watertight slip-on boot (Item 17). The tension link is surrounded by white mineral oil and is enclosed by a bladder (Item 16). This allows the system to be pressure-compensated.
5	End plug; fits into the end fitting (Item 1). The electrical conductors pass uninterrupted out of the electromechanical cable, through the end plug (Item 5), through a watertight slip-on boot (Item 17), through the tension link tube (Item 4), through the end plug (Item 6), through a watertight slip-on boot (Item 17), and back into the electromechanical cable.

The operation of the tension load cell is standard. The load is applied at the end termination (Items 1 and 2). The tension link (Item 4) is deformed, and the stress in the link (Item 14) is measured. The fabrication material is steel for Items 1, 2, and 4; PVC for Items 5 and 6; and rubber for Items 4 and 17.

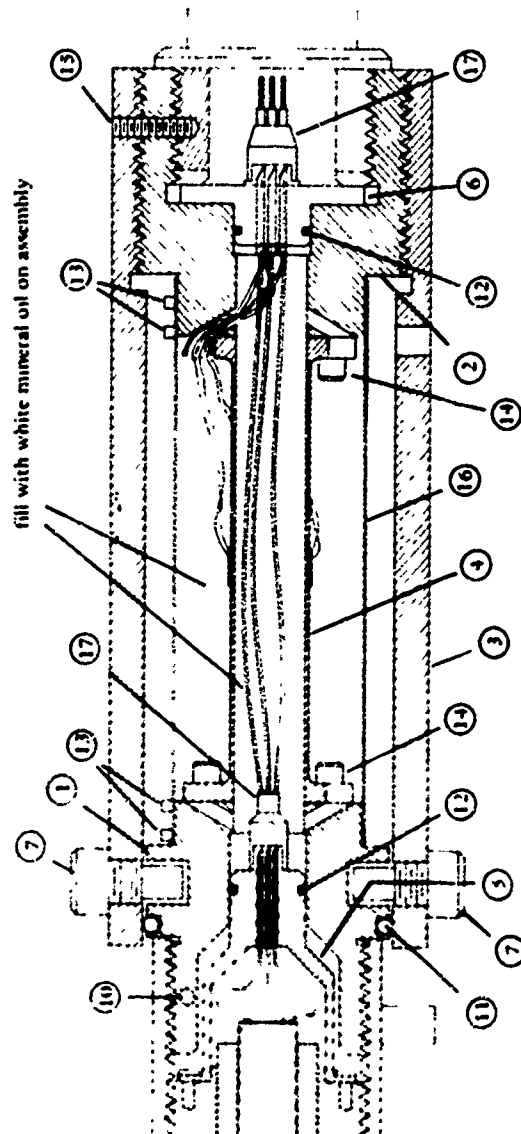


Figure B-1. Underwater tension load cell.

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